## Ground-penetrating radar at Chaco Canyon, USA, 1974 - 1976

Several archaeological sites at Chaco Canyon, New Mexico, were explored with a ground-penetrating radar that was developed and operated by the staff of Stanford Research Institute (SRI); these individuals included: Roger Vickers, Robert (Bob) Bollen, David Johnson, John Tanzi, and Howard Young. This is a summary of those surveys. These experiments were done in 1974, 1975, and 1976. Chaco Canyon is located in the southwestern part of the USA and near the northwestern corner of the state of New Mexico.

Blue text marks hyperlinks to figures or other reports within this PDF document. The text here has been digitized from a paper print of the published article and also each report; a few additional notes are included between [brackets].

### First survey

The first survey was done on October 3 - 4, 1974. The findings of this survey were published in the MASCA Newsletter (Museum Applied Science Center for Archaeology at the University of Pennsylvania Museum in Philadelphia) in an article dated 1975 (volume 11, number 1). A copy of that article is here; copies of the original figures for that article are included. Dimensions are sometimes in feet (ft) in this article; if so, multiply those distances by 0.3 to convert them to meters.

This 1974 survey was done at three locations within Chaco Canyon. The major site of Pueblo Bonito is located on a map of the area. Hungo Pavie is another large (but unexcavated) Chacoan house; it is located about 3 km southeast of Pueblo Bonito. The site called Marsha's Pit House was near these other sites; this was an informal name that does not appear to be applied at Chaco Canyon any longer.

### Second survey

The second radar survey was done at Pueblo Alto, which is about 1 km north of Pueblo Bonito. Both sites are located in a map and Pueblo Alto is also shown in an aerial photograph. This survey was done in the span of 23 - 26 September 1975.

Seven photographs that illustrate the second year of the experiment are included here. The photos reveal the large electronic instruments that were required for a radar then: A pulse generator to synchronize all of the equipment, a dual or bistatic antenna for the transmitter and receiver, a sampling oscilloscope for converting the radar echoes to a low frequency that could be recorded, a tape recorder that can store the now-low frequency radar pulses, and a paper-strip recorder for an immediate view of the radar profiles. All of these items are in modern radars; most of them are now small and

hidden from view in simple boxes.

Shortly after this radar survey was finished, the archaeological excavation of Pueblo Alto began; the excavation reports are in several volumes titled "Investigations at the Pueblo Alto Complex, Chaco Canyon, New Mexico, 1975-1979", and these are available at either of these two web sites:

https://archive.org/details/investigationsat01math/mode/2up

http://www.chacoarchive.org/media/pdf/002125.pdf

Pages 19-20 of volume 1 of these reports mentions that excavations confirmed the findings of the radar survey, although the area of survey was too small to be of much assistance.

**Third survey**

This survey was done in the spring of 1976; while the work was also done at Pueblo Alto, there were significant changes to the equipment. First, the cable to the radar antenna was eliminated, with telemetry of the echo signals by a radio link from the antenna cart to the nearby and stationary recording equipment. Second, the location of the radar cart was automatically determined with a positional locating system having reference radio transmitters at three fixed locations. A proposal for an efficient radar that is similar to the actual equipment is included here as "A radar and multisensor system for archaeological exploration".

Details about this 1976 survey, and a summary of the two earlier surveys, are found in a report that is included here, titled "Archaeological investigations at Chaco Canyon using a subsurface radar". A somewhat different version of that report is available on the web at the Internet Archive:

https://archive.org/details/remotesensingexp00lyon/.

See pages 81 - 101 in that large report for the radar report mentioned above.

During the period of this work at Chaco Canyon, another member of the SRI staff, Lambert Dolphin, experimented with a related (but lower frequency) ground-penetrating radar for deep exploration within several pyramids in Egypt; he also tested a variety of geophysical instruments at other archaeological sites in Egypt. His two reports on those surveys are:

Electromagnetic Sounder Experiments at the Pyramids of Giza

Applications of Modern Sensing Techniques to Egyptology

These reports are available at his web site:

http://ldolphin.org/egypt/

**After these surveys**

Two additional ground-penetrating radar surveys have been done at Chaco Canyon in recent years:

Lowry, Sarah M., 2009, Using Ground-Penetrating Radar to Study the Bluff Great House: History and Regional Interactions from A.D. 200 to 1300, Master of Arts thesis, University of Denver, Colorado, USA. Available at:

https://digitalcommons.du.edu/etd/382

Sturm, Jennie O., 2019, Using Archaeological Remote Sensing to Evaluate Land Use and Constructed Space in Chaco Canyon, PhD dissertation, University of New Mexico, Albuquerque, New Mexico, USA. Available at

https://digitalrepository.unm.edu/anth_etds/183

Roger Vickers continued his work with airborne and other ground-penetrating radars after he left SRI; his company is International Radar Consultants, and its web site is: http://www.int-radar.com/

Lambert Dolphin started West Coast Locators, Inc. (a geophysical exploration company) after he left SRI; he is now retired and maintains the large web site at:

http://ldolphin.org/

# A communication on an archaeological radar experiment at Chaco Canyon, New Mexico

Roger S. Vickers and Lambert T. Dolphin
Stanford Research Institute, Menlo Park, California

## BACKGROUND

In October 1974 a joint experiment was conducted at Chaco Canyon, New Mexico, to determine whether ancient buried Indian structures could be detected by means of a suitable radar system traversing the surface. The research team consisted of personnel from the University of Pennsylvania Museum Applied Science Center for Archaeology; the Department of Anthropology, University of New Mexico (in cooperation with the National Park Service); and Stanford Research Institute.

Chaco Canyon is situated in the northwest corner of New Mexico and is the site of a number of Indian ruins dating back to about A.D. 600 in various stages of excavation. Some dwellings have been excavated and then backfilled, with the result that accurate maps of the structures are available. Other areas consist of completely undisturbed overburden containing obvious extensions of buildings already exposed. The site is therefore ideal for testing new techniques in that there is considerable knowledge of the location of the buried structures. Chaco Canyon is ideal for radar experiments from another point of view also. The soils that form the cover For the Indian ruins are extremely dry and have remarkably low microwave losses. Radar signals can therefore penetrate into the soil with little loss or dispersion. This condition is rarely found except in solid rock.

Samples of the local soils and the building materials used by the Indians were obtained from the site and analyzed by SRI. Their microwave properties are shown in Table I (see Footnote 1), and were sufficiently encouraging that it was agreed to mount a field experiment at Chaco Canyon to obtain radar signatures of some of the buried ruins. The radar system used employed a center frequency of 400 MHz, with the provision for operating at other frequencies if necessary. The resolution of the system at this frequency was not better than 1 ft. The mode of operation was to house the electronics and display system in a panel truck (Figure 1) and to run cables out to the antennas which were mounted on a small hand cart (Figure 2). The cables allowed a radius of operation of about 150 ft, which was sufficient for most of the sites surveyed. Data were recorded on an instrumentation recorder in the truck and brought back to SRI for further processing. The data could be assessed on site only by viewing the oscilloscope screen.

Traverses were made with the radar system at the following sites:
Pueblo Bonito (the Great Kiva, backfilled)
Pueblo Bonito (the city wall, undisturbed)
Marsha's Pit House (backfilled)
Hungo Pavie (undisturbed area close to main ruins).

## RESULTS

### Pueblo Bonito

A number of traverses were made over an area that included a vertical structure referred to as the city wall. Excavation a short distance away revealed the wall to be about 1 ft wide, 4 inches below the surface, oriented normal to the traverse direction, and in a good state of preservation. Our radar had a dead time of 5 nanoseconds (ns), corresponding to the first one foot of record, so the wall may not have been an entirely suitable target since it was so close to the surface. The processed data showed a large number of subsurface features that were difficult to interpret. However, one of the more conspicuous features was at the location of the wall. It appears from the radar data that there was more than one structural feature along the traverse, and in addition a great number of smaller point reflectors - probably scattered building materials - were near the surface. Since map-printing equipment was not present on this field trip it is difficult to verify all the targets identified by radar. In future experiments some form of mapping, however crude, will be incorporated on the site. A photograph of one of the traverse radar maps is given in Figure 3. The interpretation on the figures in this report is based on our knowledge of the area and our experience with radar echoes from similar subsurface targets at other sites. The vertical scale in Figure 3 is approximately 5 ft (full scale).

The plaza of Pueblo Bonito contained an area that covered a Great Kiva, previously excavated and now back-filled. Several traverses were made over the kiva in order to see if the radar could detect the perimeter walls. As in the case of the city wall, the construction materials consisted mostly of sandstone and a form of mortar. The traverses were measured from the south wall extending over the center of the kiva and onto the far wall. The radar records show a discontinuity about 2 ft in width at 70 ft out from the south wall, and a narrow vertical structure, probably 1 it or less in width and 4 to 6 ft down at 90 ft out. Estimates by the archaeologists at the site placed the buried wall at about 90 ft, but no estimate of depth was made. We did not succeed in distinguishing the radar echo from the near (southern) kiva wall because of the multitude of other echoes coming from structures related to the south city wall of Pueblo Bonito.

### Hungo Pavie

The area traversed at this site was to the best of our knowledge undisturbed, and crossed a prominent mound containing an extension of the main structure. The mound was some 15 to 20 ft in width and was surmised to contain rooms as well as a portion of the city wall. The radar results for this site were the most successful that we obtained anywhere at Chaco Canyon. A portion of the radar record is shown in Figure 4. The vertical extent of this record is about 12 ft, and the horizontal extent about 20 ft. Vertical structures with interconnecting horizontal members are clearly depicted and indicate a man-made origin. From the scale it is obvious that the horizontal sections are not the floors of successive stories as was first thought, but more probably different levels of partially decayed walls.

### Marsha's Pit House

This area was a backfilled site covering an adobe pit house. The dimensions and exact

location of the walls were unknown. Figure 5 shows one complete traverse from the pit house site. It is quickly seen that there are no striking features like those in the records from Hungo Pavie, but nevertheless some evidence of a buried wall is present at 78 ft, and shallow echoes are present at 47 to 50 ft, and at 66 to 68 ft. We did not expect too much success at this site since the dielectric contrast between adobe and the fill material is minimal.

## CONCLUSIONS

The simple radar system that was used at Chaco Canyon produced some very promising results, and more importantly pointed to a number of improvements in design that would greatly enhance the performance of a radar system designed expressly for archaeological work. It should not be forgotten that the Chaco Canyon area was not typical of conditions encountered throughout the USA in that the soils were extremely dry and nonconductive. In many wetter areas the radar would stand no chance at all of producing high-resolution results, and one would be forced to resort to methods more similar to resistivity surveys in their frequency content, with attendant loss of resolution. In any case, simple measurements of content can be made in the laboratory in advance of field work to determine the usefulness of radar at a given archaeological site.

The use of radar techniques in archaeology should certainly be pursued further, with more field tests over undisturbed areas and subsequent follow-up to determine the actual position of structures located by the radar system. Further, more extensive work at Chaco Canyon is an attractive possibility. With the knowledge gained during our first expedition a more definitive experiment could be designed and conducted.

## ACKNOWLEDGMENTS

The cooperation of Mr. James Mount, Park Ranger, Chaco Canyon National Monument, is gratefully acknowledged. The field support of Dr. Thomas R. Lyons, University of New Mexico, and Mr. Bruce Bevan, University of Pennsylvania Museum Applied Science Center for Archaeology, were essential ingredients to the success of the experiment.

Footnote 1

Radars suitable for subsurface probing can operate with an overall dynamic range of about 10 orders of magnitude (100 decibels). A loss factor of 2 decibels per meter therefore implies that the radar can detect reasonable targets at depths to approximately 25 meters or so. As can be seen from Table 1, losses decrease with decreasing frequency, so low frequencies are desired for maximum depth of penetration. However, high radar resolving power implies high frequencies, so generally a compromise between losses and resolution must be made.

This article was published in the MASCA Newsletter in 1975 (volume 11, number 1). The text here has been digitized from the printed version. The original figures are here; extra information has been added to the captions in [brackets]. Blue text marks hyperlinks.

TABLE I

RADIO FREQUENCY ATTENUATION FACTOR FOR SAMPLES I THROUGH IV*

| Frequency (MHz) | Attenuation, in decibels per meter (dB/m) | | | |
|---|---|---|---|---|
| | $\alpha_1$† | $\alpha_2$ | $\alpha_3$ | $\alpha_4$ |
| 10 | 0.24 | 0.20 | - | 0.33 |
| 20 | 0.45 | 0.45 | - | 0.64 |
| 30 | 0.60 | 0.66 | - | 0.90 |
| 40 | 0.83 | 0.82 | - | 1.2 |
| 50 | 1.0 | 1.0 | - | 1.4 |
| 60 | 1.3 | 1.2 | 11.7 | 1.4 |
| 70 | 1.4 | 1.4 | 14.2 | 1.7 |
| 80 | 1.5 | 1.5 | 16.2 | 1.9 |
| 90 | 1.8 | 1.7 | 19.6 | 2.0 |
| 100 | 2.0 | 1.8 | 22.0 | 2.1 |
| 120 | 2.6 | 2.2 | 24.3 | 2.5 |
| 140 | 3.2 | 2.8 | 30.1 | 2.9 |
| 160 | 4.1 | 3.2 | 36.1 | 3.4 |
| 180 | 4.4 | 3.4 | 43 | 3.8 |
| 200 | 5.8 | 3.5 | 55 | 4.2 |
| 220 | 7.4 | 3.8 | 69 | 5.2 |
| 240 | - | 5.1 | 86 | 6.2 |
| 250 | - | 5.7 | - | 7.5 |

*Sample I: Construction sandstone, Pueblo Alto, average dielectric constant, $\varepsilon_r$ = 4.9 to 6

Sample II: Alluvial sand, Pithouse E, $\varepsilon_r$ = 1.7 to 2.1

Sample III: Alluvial clay Chaco Wash, $\varepsilon_r$ = 7.0 to 12

Sample IV: Alluvial loam below trash dump, $\varepsilon_r$ = 1.6 to 2.4

†where $\alpha = 0.012834\ f \sqrt{\varepsilon_r}\ \{ \sqrt{1 + \tan^2 \delta} - 1 \}^{\frac{1}{2}}$ dB/m

Figure 1. Radar system mounted in panel truck
[The recording and control equipment for the radar in 1974. From right to left are a four-channel FM instrumentation tape recorder, a pulse generator, and a sampling oscilloscope (with a Polaroid camera mounted for photographs of the radar echoes).]

Figure 2. Chaco Canyon antennas on hand cart
[The antenna of the ground-penetrating radar. It is being pulled along a line in order to record a echo profile; the transmitter and receiver are in separate metallic enclosures on the cart. Jim Ebert is pulling the cart; at this time, he was at the Chaco Center in Albuquerque studying the application of remote sensing to archaeological sites. He later started his company, Ebert and Associates, where he continues his work on remote sensing and GIS. Behind the antenna, Howard Young from SRI is organizing the electrical cables that extend between the antenna and the recording equipment, so that they do not snag on bushes or stones.]

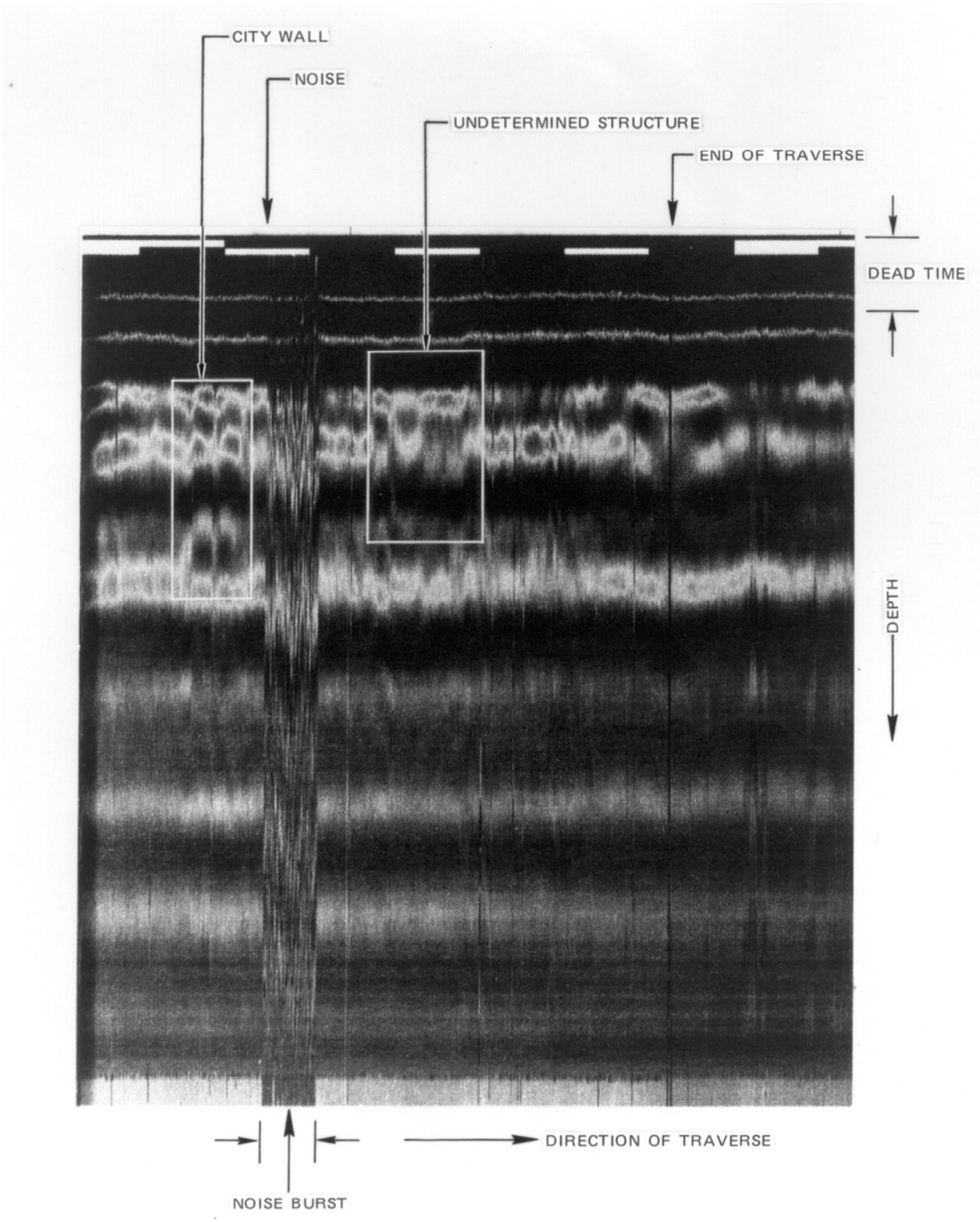



Figure 3. Radar data from Pueblo Bonito (over city wall)
[One of the radar profiles. While the continuous horizontal bands are not important, several distinct changes in those echoes reveal a known wall and another feature. The noise shown here may be caused by another transmitter being operated in the vicinity.]

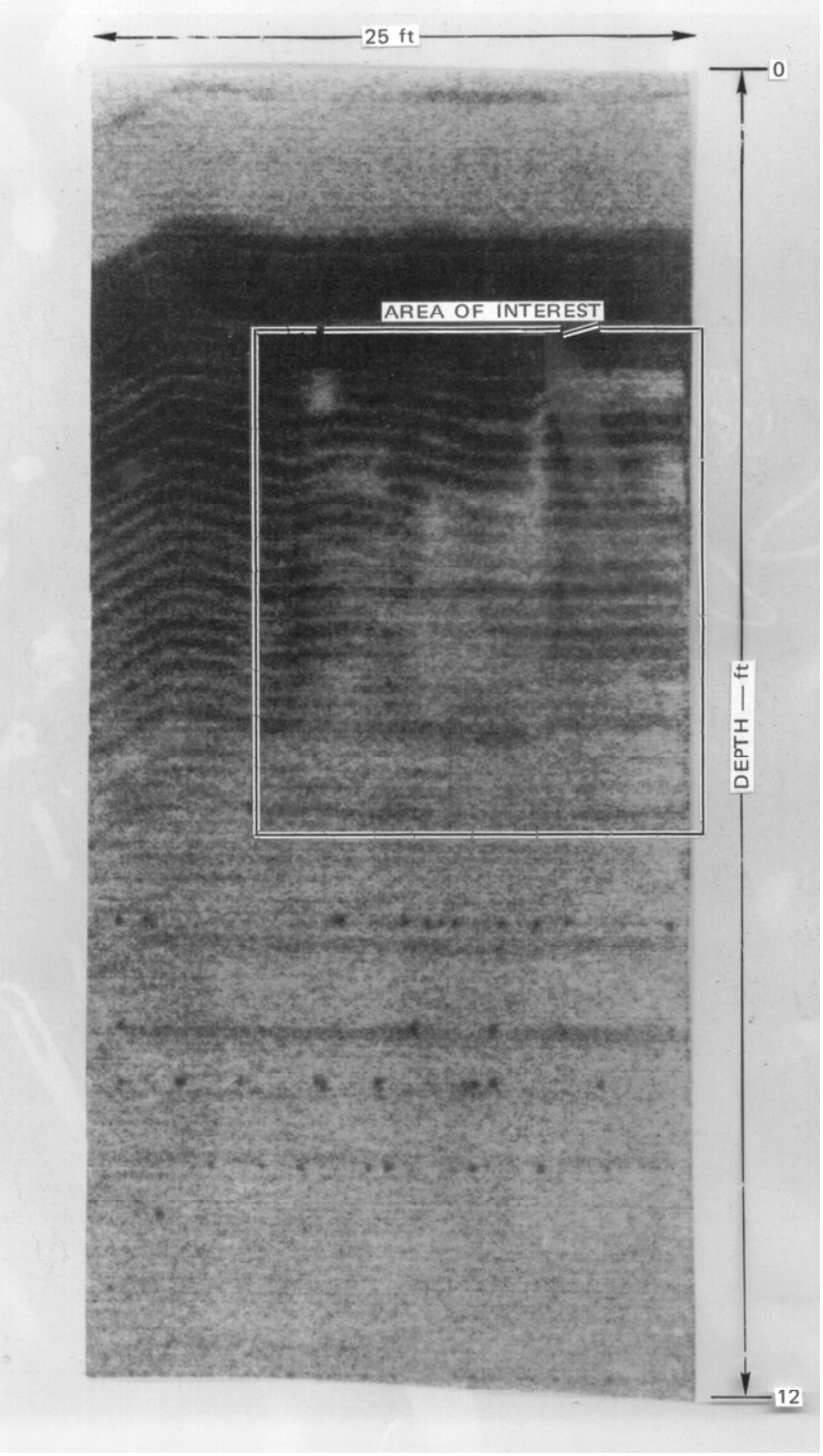



Figure 4. Unprocessed data from traverse at Hungo Pavie
[Another radar profile. This has detected a change in stratification at a depth of about 1 m. As with almost all radar profiles, the horizontal scale is compressed relative to the vertical scale; this horizontal compression is a factor of about four here.]

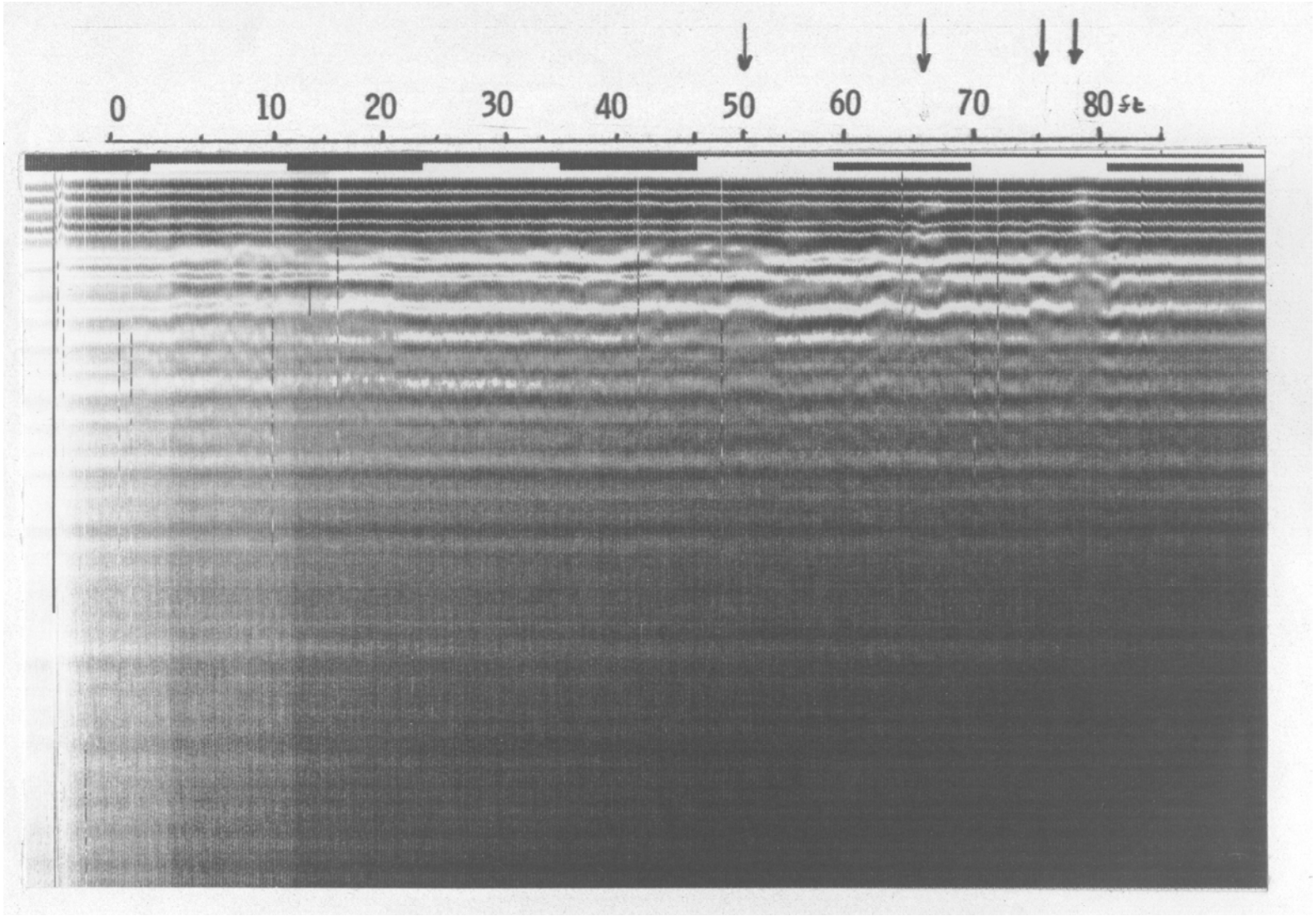
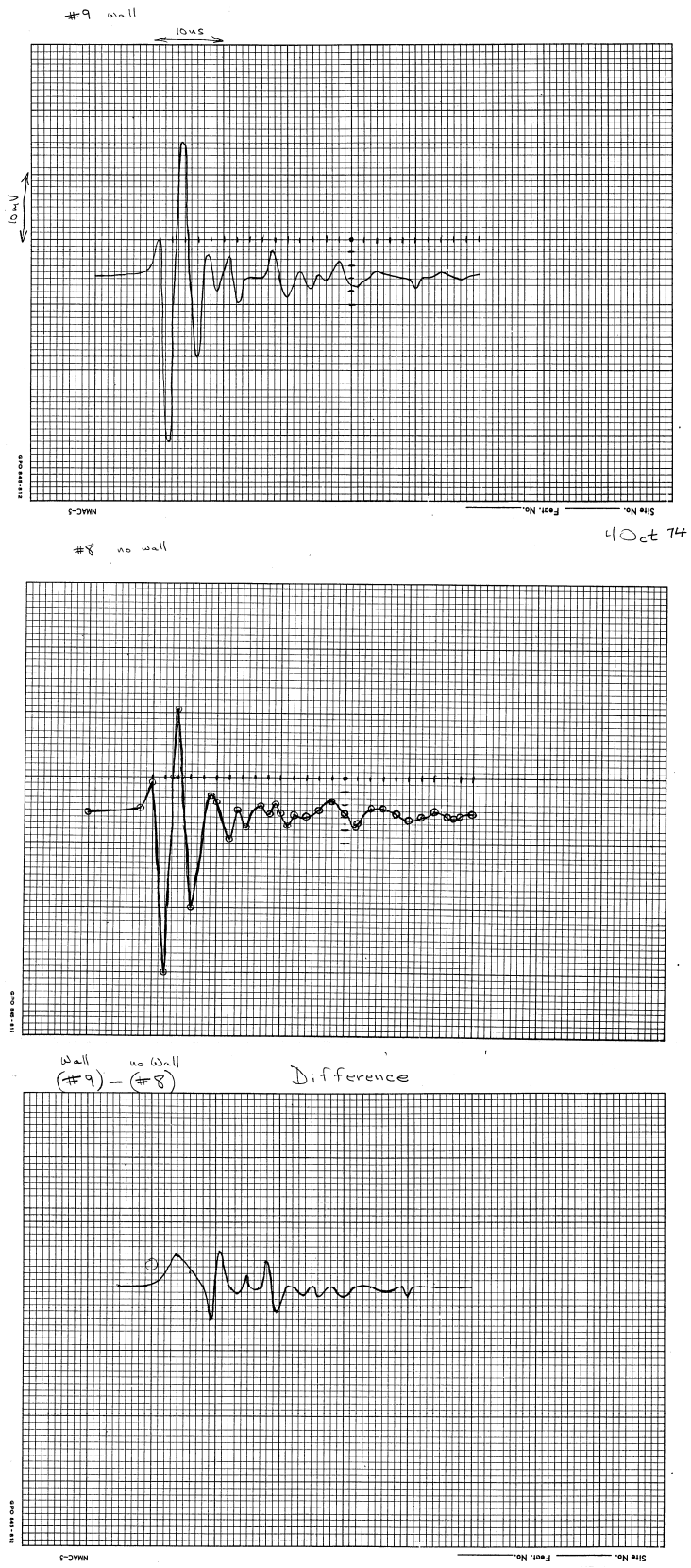



Figure 5. Data from traverse over Marsha's Pit House
[Several small echoes are marked with arrows. These may be caused by shallow stones or other contrasts within the soil.]




[Figure 6: A comparison of radar echoes. While it was not possible to create two-dimensional images of the radar profiles in the field, photographs of vertical scans from the radar could be compared by digitizing them and subtracting with simple arithmetic. This example shows the difference in the echo from a known buried wall as compared to a nearby location where there was no wall. This illustration was not in the MASCA Newsletter.]

The locations of the ground-penetrating radar surveys. Most of the work was done at the two sites marked with black arrows: Pueblo Bonito (in 1974) and the Pueblo Alto Complex (in 1975 and 1976). This is a modification of a map from the Chaco Culture National Historic Park. The ground width in this view of the map is 6.5 km; north is upwards.

An aerial photograph of Pueblo Alto. Remnants of some walls are still visible. The length of this D-shaped building is about 110 m; it has about 130 rooms and 18 kivas and it was constructed in about 1100 AD. This photograph was taken on 27 April 1972 for Tom Lyons at the Chaco Center for his aerial study of the ancient roads at Chaco Canyon; the ends of several of those roads are visible as dark lines pointed toward Pueblo Alto on the left side of this photograph. Pueblo Alto looked the same in 1975, when the ground-penetrating radar survey was done in the plaza here. Shortly after that survey, however, a large archaeological excavation exposed the buried walls at this site.

1975 Figure 1: Unloading the radar. It arrived via air freight from California. Tom Lyons from the Chaco Center is wearing a cowboy hat; he worked for many years on remote sensing at Chaco Canyon. John Tanzi, on the right, is unpacking an oscilloscope. A pair of horn antennas are in the foreground; this bottom view shows their aluminum construction. An ancient refuse dump at Pueblo Alto is visible as the mound on the right. Photo 23 September 1975

1975 Figure 2: Assembling the radar equipment. Roger Vickers is testing one of the two horn antennas. The radar pulse will travel downwards from the transmitter at the top and be beamed into the soil through the pyramidal cone. While some of the instruments for the radar were from companies such as Hewlett-Packard and Tektronix, the antennas and their associated electronics were developed by SRI. Photo 23 September 1975

1975 Figure 3: Recording and display equipment. The sampling oscilloscope (on the right) will display a single depth scan from the radar. The radar signals were also stored with the four-channel FM (frequency modulation) recorder on the left. The oscilloscope converted the high frequency echo from the radar to an audio frequency. Since that frequency can be very low, a special type of recorder is needed; an FM recorder can record down to a frequency of zero. Photo 23 September 1975.

1975 Figure 4:  Recording a radar profile.  Bob Bollen is pulling the pair of horn antennas on a cart, while John Tanzi monitors the recording of the data at the van.  The ground at this site is mostly bare soil, with some bushes and grass; the surface is rather level within the plaza of Pueblo Alto.  Photo 25 September 1975.

1975 Figure 5:  A different antenna.  The bistatic pair of horn antennas have been replaced with a bow-tie antenna; this looks like a flat board on the bottom of the cart. Roger Vickers pulls the radar along a traverse; several long cables connect the antenna to the control and recording equipment in the van.  Photo 24 September 1975.

1975 Figure 6: The paper chart of a radar profile. The printer is at the upper side of the photo. No printer like this was available during the 1974 survey at Chaco Canyon; this printer greatly aided the understanding of the radar profiles during the survey. Photo 25 September 1975.

1975 Figure 7:  Annotating a paper print.  John Tanzi is adding some notes to a radar profile.  This photo also shows a second oscilloscope (just above Johns's head), and a pulse generator just above that.  The tape recorder shown in Figure 1 is to the right.  Photo 25 September 1975.

SRI Stanford Research Institute
Menlo Park, California 94025 • U.S.A.

Technical Memorandum December 1975

# A RADAR AND MULTISENSOR SYSTEM FOR ARCHAEOLOGICAL EXPLORATION

Prepared by
Lambert T. Dolphin, Jr.
John D. Tanzi
Roger S. Vickers

## I INTRODUCTION

The Radio Physics Laboratory at SRI has for the past several years been exploring up-to-date, subsurface remote-sensing methods for applications in mining, geophysical exploration, glaciology, and archaeology. Especially in the field of archaeology, where excavation must necessarily be slow, careful, and systematic, we believe that these advanced mapping techniques can provide the archaeologist with helpful guidelines and indicators that can save both time and money during subsequent digging.

This memorandum describes briefly a versatile remote-sensing system especially designed for archaeology, utilizing initially a subsurface radar system as primary sensor. The system, which operates on a roving platform on the surface, incorporates automatic position-plotting, telemetry, and data-analysis units. Other sensing devices can be added to the platform with or without the use of radar simultaneously. Surveys with all types of sensors can thus be conducted much more efficiently than has previously been possible, since all the housekeeping data are recorded automatically (e.g., position, time, and sensor configuration).

Initially, the sensor and telemetry package will be mounted on a hand-towed cart similar to units previously used by our laboratory in experiments at the Chaco Canyon, New Mexico archaeological site. Typically, the cart will carry the subsurface radar transmitter and receiver, analog-to-digital converter, telemetry transmitter, and position-locator transmitter. These units will all be very small solid state models, battery-powered. Later, a back-packed man-portable unit will be built so that surveys using a magnetometer, resistivity meter, induced-polarization set, electromagnetic (Slingram) probe, microgravity meter, or acoustic sounder can all be conducted by one or two men simply by walking over the area to be surveyed, pausing at intervals to emplace sensors, and pushing a button to transmit data to a remote van for real-time plotting. Position coordinates of the sensor would also be transmitted to the van and plotted simultaneously.

Illustrative of our work in subsurface remote sensing has been our development and application during the past three years of a family of ground-penetrating radars. Recent experiments[1, 2, 3] have shown that suitable radars can often be useful in mapping archaeological sites in advance of excavation. Such radar surveys can be conducted rapidly,

given suitable equipment designed for the purpose, and although a complete inventory of subsurface features is rarely possible, preferential areas for excavation can often be delineated.

Just as other remote sensors used in archaeology have their limitations, so also does radar. Soils and rocks near the earth's surface frequently exhibit very high radio frequency losses because of moisture content and porosity. Losses in some soils can at times limit penetrability of the radar signal to a foot or less, in which case radar is unsuitable for learning anything useful about subsurface features. More typically, however, one can hope to penetrate several feet into even relatively moist soils.

Fortunately, radar potential at a given site can be readily assessed in advance by a few simple laboratory tests on representative soil samples from the site. Such samples give a reasonably good assurance of the radar penetrability of the overburden at the site. In addition, on-site resistivity measurements made by the local field teams can provide even more definitive data.

Figures 1 and 2 show examples of radar data displays and typical subsurface features of interest, to illustrate the type of subsurface records obtainable. Figure 3 shows a subsequently excavated wall corresponding to one of the radar echoes.

In those instances where radar is unsuitable, we have found that complementary sensors can frequently be useful. For example, when radio frequency losses are excessively high, an acoustic sounder can probably prove useful in many situations.

Acoustic sounders are now under development at SRI and will be field-tested in the very near future. Other sensors suitable for use in archaeology are simple to build or available commercially. Two or more sensors can be simultaneously fed into the portable-unit telemetry link for a multisensor survey of an archaeological site without the necessity of repeatedly walking the survey area. None of the sensors will disturb the site in any way beyond trampling grass or perhaps the removal of an occasional bush.

A further sensor type that has great applicability to this problem, as well as being compatible with the sensor platform described, is the continuous-wave (CW) induction method, in which the mutual coupling between two coils is monitored. In essence the system, which is well known in standard geophysical application, acts like an electrodeless resistivity system, but employs much the same components as the sub-surface radars, with coils replacing the antennas and a CW source replacing the pulse generator. The output contains information on the conductivity of the underlying soils, and can be made to give adequate spatial resolution in the horizontal plane.

## II RADAR DESIGN CONSIDERATIONS

Radars for subsurface remote sensing differ greatly from conventional radars that track aircraft, missiles, or hurricanes. Firstly, the targets to be measured are often only a few feet from the antennas--requiring a radar pulse width only one or two RF cycles in length. Such a short pulse implies a very wide system bandwidth, typically hundreds of megahertz.

It is essential that the antennas used for transmission and receiving couple well into the earth but poorly into the air above; otherwise, not only will subsurface propagation be

poor, but unwanted and confusing echoes from targets above the ground will be found on the records.

Subsurface radars are not able, furthermore, to achieve as great a dynamic range (ratio of transmitted power to minimum detectable received power) as conventional radars. The latter are signal-to-noise-limited, and can achieve 20 orders of magnitude (200 decibels) dynamic range in many uses while subsurface radars are limited to 100 dB or so by unwanted echoes (clutter), obscuring the same apparent radar ranges as the desired echoes. Because of the usually deleterious clutter, some form of clutter reduction is highly desirable. The use of two receiving antennas and signal subtraction is one means of clutter reduction. Because of the signal-to-clutter-ratio limit, higher peak powers are not generally necessary in subsurface radars. Increasing the power raises the clutter and and echo strength equally. However, there is no state-of-the-art limitation in power. A few kilowatts can be generated readily, and 1.2-MW transmitters were used in an attempt to explore the pyramids of Giza[4].

An important factor in archaeological radar design is choice of operating frequency. A high operating frequency gives high resolution and sensitivity to small targets. However, attenuation in the medium generally rises rapidly with frequency and a compromise between resolving power and penetrability is usually necessary. For archaeological work a radar frequency between 100 MHz and 400 MHz is usually suitable. At 100 MHz the probing wavelength in the earth medium is approximately one meter if the soil is damp, and at 400 MHz, about one-fourth meter. In very dry soils typical wavelengths are about 1.5 m and 0.4 m, respectively. It is reasonable to expect resolution of two objects less than a foot apart at such frequencies, meaning that one can see walls, tunnels, graves, boulders, and so forth when the attenuation loss is moderate or low.

Experience with operation of subsurface radars has shown that the principal operating cost for a radar survey is the professional manpower required for laying out a grid, setting up and operating the radar, and interpreting the data. It is therefore our belief that the next step toward making underground radar (and other advanced sensor devices as well) useful and economical in archaeology is to incorporate three automatic features. The first of these is electronic measurement of the portable-unit position, eliminating survey and grid staking altogether. The second is telemetry of the sensor data to a nearby van, in which case all cables to and from the cart can be eliminated--the portable unit becomes cordless and thus easily hand-towed, or back-packed. Not only is the cordless feature desirable from a maneuvering standpoint, but also coaxial cables to and from the portable unit can, at times, perturb the data and introduce spurious results into the records. Furthermore, the position measurement (with grid plotter) and telemetry link mean that other sensors, such as magnetometer, resistivity meter, acoustic sounder, etc., can be plugged into the portable unit either separately or simultaneously so that data from these other sensors can be recorded as rapidly as radar data.

The third highly desirable feature of the sensing system is an integral minicomputer that computes the portable-unit position and plots it on a grid in real time, and, at the same time, processes the radar data and prints a display of the results. Most of the data interpretation can thus be done in the field, and the results are available in permanent, easy-to-read formats that archaeologists can use with a minimum of training. Tedious and

expensive manual examination of the data is eliminated, as is the expensive tape recorder required if all the data processing is to be done "back at the lab." Should the data reveal interesting hot spots, further detail can be obtained by surveying the area of interest with a tighter pattern while all the equipment is still set up and running. Thus there will be no need for later resurveying.

The radar, other sensor inputs, and position-measurement data will be all digital and telemetered on a time-share basis. This means that the possibility of interference between these systems is eliminated; furthermore, the telemetry-link requirements are greatly simplified.

Figure 4 is an artist's sketch of the proposed sensor-system configuration. As can be seen, the position-measurement equipment is deployed in the general area to be studied; the portable unit is wheeled, towed, or back-packed across the area in any kind of systematic or random grid desired, while the van-mounted equipment prints out, in real time, portable-unit position and processed data from the sensors. The field crew need be only two men--a portable-unit operator and a van operator. For surveys over very extensive areas, a cart-type portable unit could be towed by a jeep.

Power for the van equipment would be supplied by a small generator, and the cart would be battery-operated (recharged at night). Solid-state circuitry will of course be used throughout the entire system, and power requirements even for the van equipment -- as well as for the portable unit--will be very modest. Figure 5 shows the portable-unit configuration, and Figure 6 shows the van equipment.

## III SYSTEM DEVELOPMENT COST

SRI has already brought the state of the art in remote subsurface sensing by radar to an advanced position. The portable-unit position recorder, minicomputer unit, and telemetry system are under detailed study and preliminary design. Because we believe such a sensing system will be very useful not only to archaeologists but also any field disciplines using portable sensors over wide survey areas--for years to come--we are most interested in obtaining a grant enabling us to build a prototype system using initially a cart-mount and radar sensor.

Following assembly and checkout of the equipment we propose to evaluate the sensor system at several archaeological sites to be selected in conjunction with our colleagues from the University of Pennsylvania Museum Applied Science for Archaeology. In order to complete such an evaluation thoroughly, the field equipment will be supplemented with a laboratory-owned mini-computer system to enable sophisticated computer data processing. In this way, the selection of an eventual on-board microprocessor to replace the more bulky mini-computer can be optimized on the basis of field studies. It is expected that the field studies can lead immediately to several note-worthy scientific papers.

Our estimate is that equipment costs for the complete sensing system will be approximately $60,000. In addition, engineering and construction labor costs are estimated at approximately $65,000, or a total of the order of $125,000.

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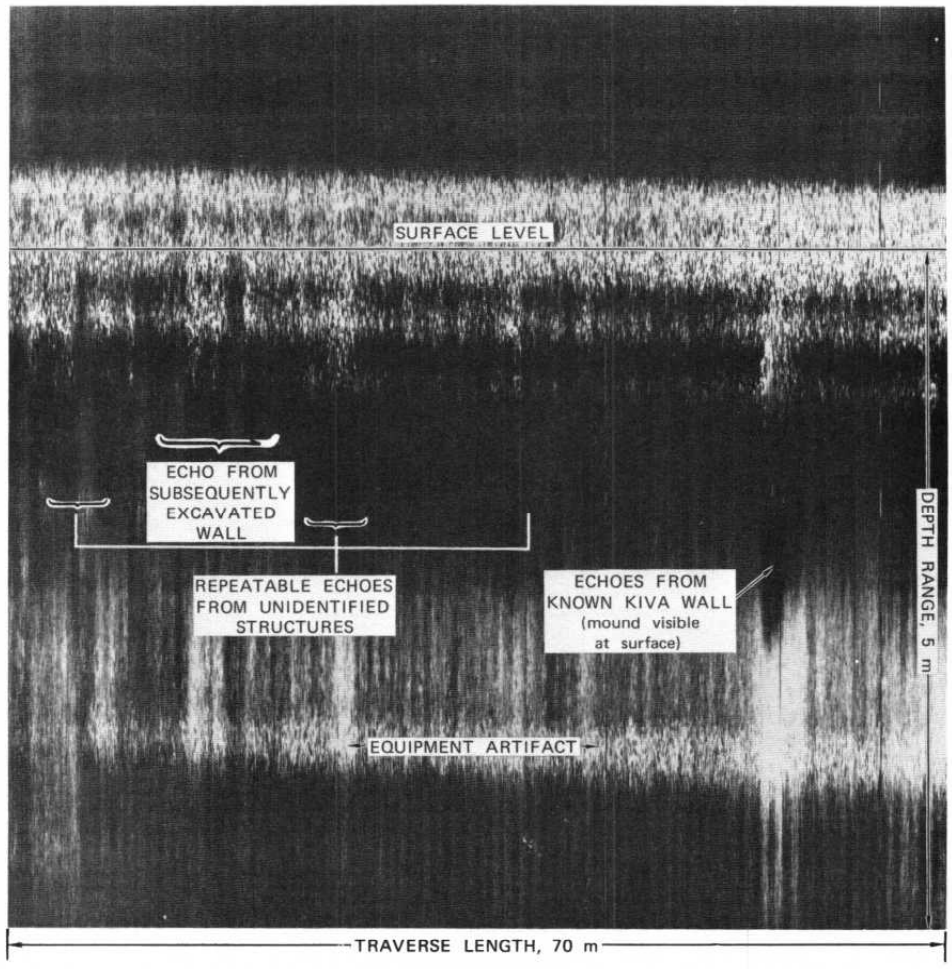
SURFACE LEVEL
ECHO FROM SUBSEQUENTLY EXCAVATED WALL
REPEATABLE ECHOES FROM UNIDENTIFIED STRUCTURES
ECHOES FROM KNOWN KIVA WALL (mound visible at surface)
EQUIPMENT ARTIFACT
DEPTH RANGE, 5 m
TRAVERSE LENGTH, 70 m

Figure 1. Radar echoes from subsurface targets – example 1

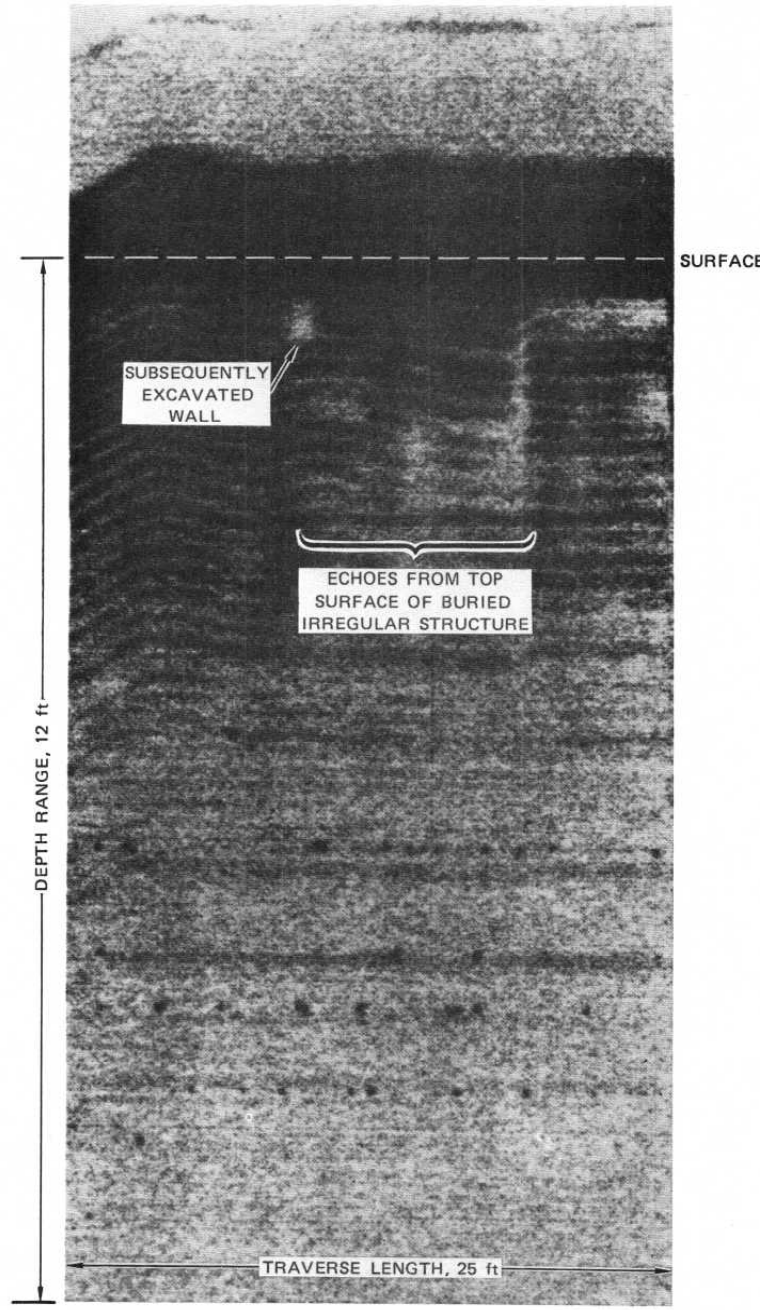
SURFACE
SUBSEQUENTLY EXCAVATED WALL
ECHOES FROM TOP SURFACE OF BURIED IRREGULAR STRUCTURE
DEPTH RANGE, 12 ft
TRAVERSE LENGTH, 25 ft

Figure 2. Radar echoes from subsurface targets – example 2

Figure 3.  City wall outside Pueblo Bonito

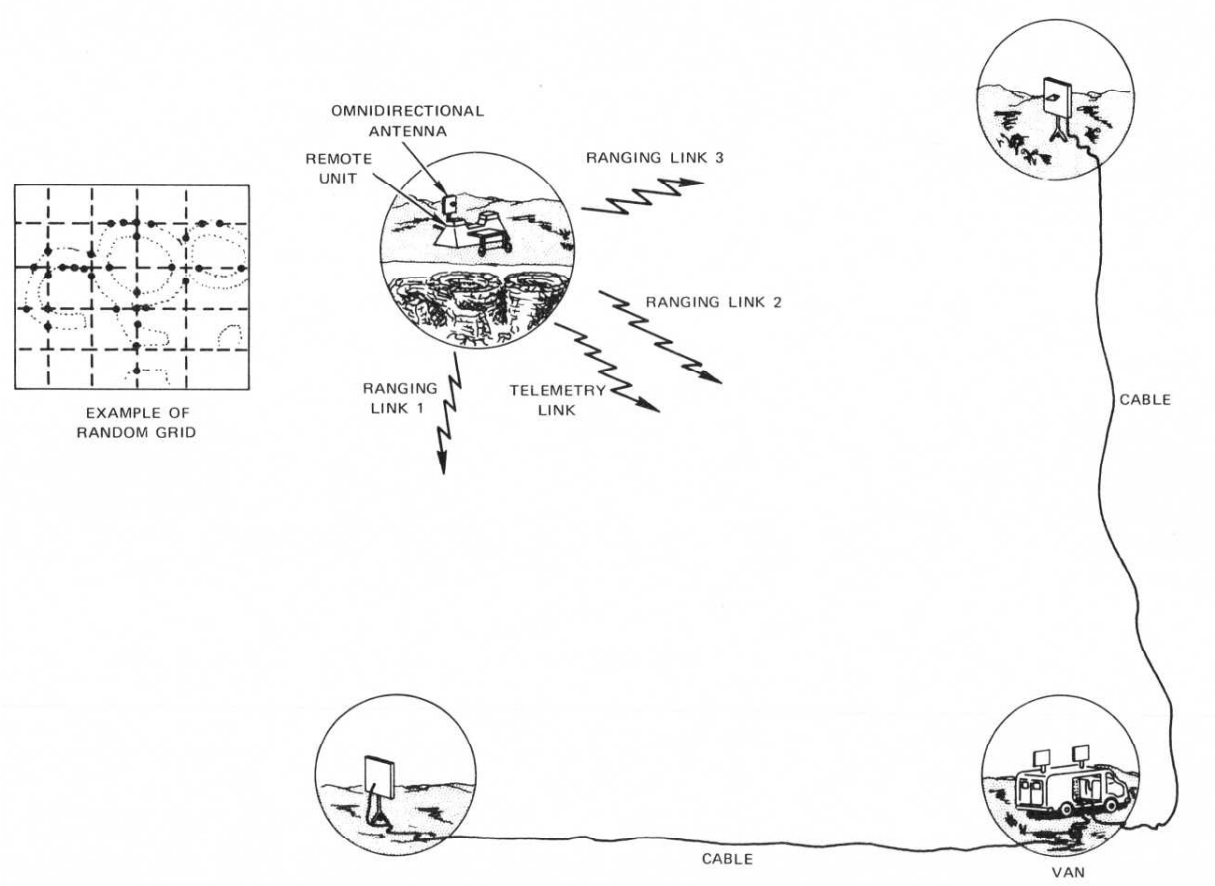


Figure 4. System configuration

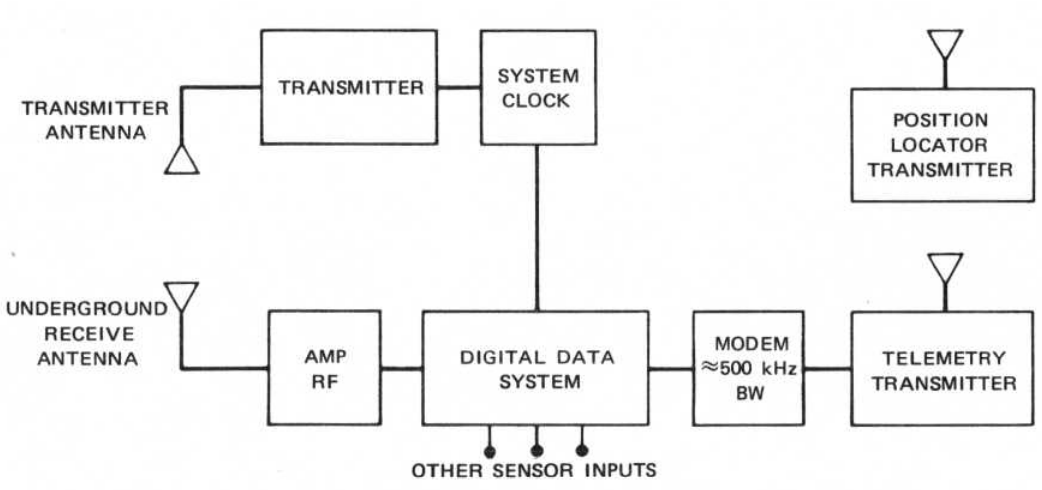


Figure 5. Portable unit block diagram

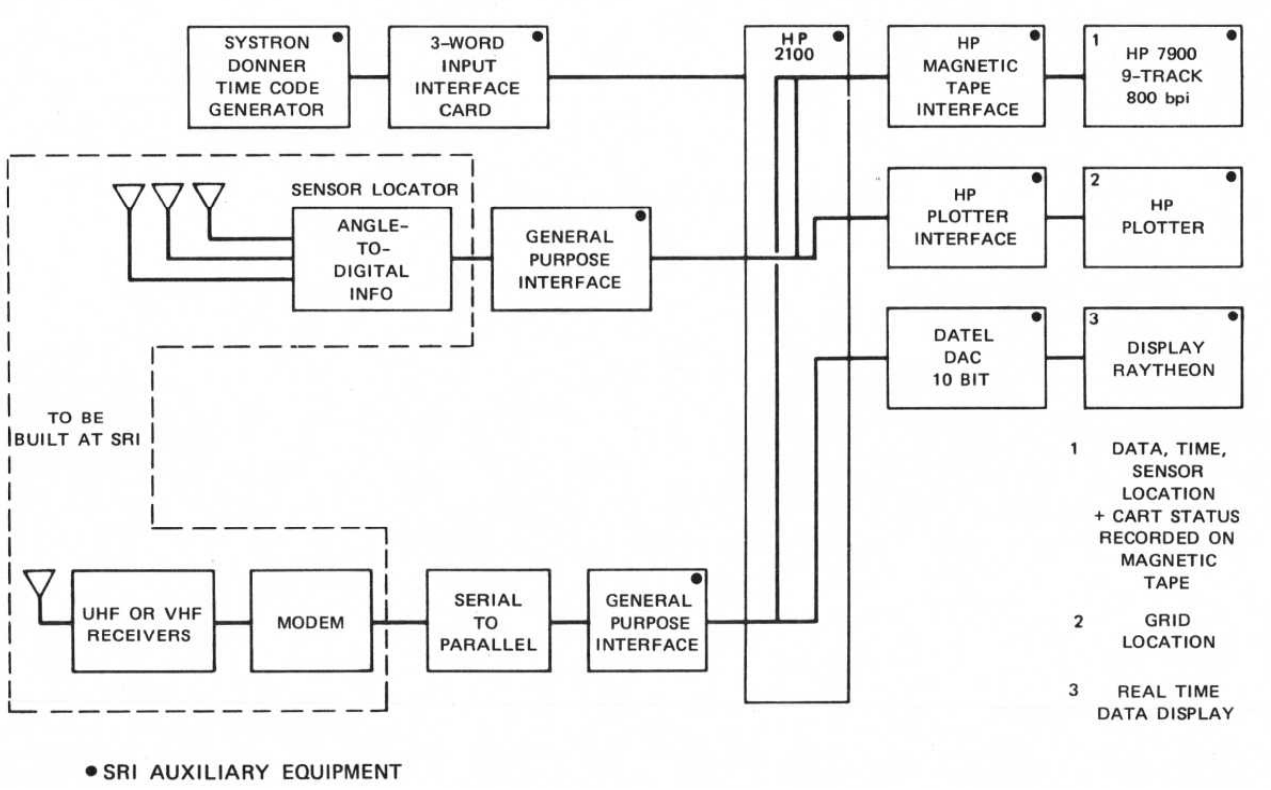


Figure 6. Van equipment

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Menlo Park, California 94025 • U.S.A.

May 4, 1976

# A MOBILE SENSING PLATFORM FOR ARCHAEOLOGICAL SURVEYING

SRI has recently completed development of a sensing platform for locating subsurface anomalies to aid the archaeologist by rapidly and nondestructively providing maps of buried features in advance of excavation. Traditionally, locating archaeological materials has been a combination of trial and error and the archaeologist's experience and intuition. Survey and excavation are highly labor-intensive methods of obtaining information in which large amounts of time, money, and energy may go into the painstaking excavation of a potential site with disappointingly few results. Indeed, if archaeological materials are found, they may not be what was sought. A single survey or archaeological excavation may cost anywhere between $10,000 and $100,000 a year, indicating the advantage of any improvements that would increase the probability of finding the often elusive archaeological objective.

The new SRI platform in use at present consists of a cordless, lightweight, hand-towed cart (Figure 1) to which any type of presently known sensing instrument for subsurface exploration can be readily attached. Such sensors can include ground-penetrating radar, and presently available magnetometers, microgravity meters, or resistivity probes. Since radar is not universally applicable to use in archaeological exploration, other complementary sensors including a high-frequency acoustic sounder are under development at present at SRI. Output from the sensing instrument is automatically transmitted by a radio link to a receiver located in a mobile vehicle parked at some convenient distance where the data are processed by a small computer, printed out within a few seconds, and digitally tape-recorded for permanent record. Simultaneous with the sensor operation, a position-location system (Figure 2) records the cart position on the horizontal plane (to an accuracy of approximately ±1 foot) and plots this information directly on a map or aerial photograph of the archaeological site. Any detected anomalies can then be superimposed on the map or aerial photograph of the site to give a readily usable presentation to guide the archaeologist in his subsequent exploration and excavation. Working hand in hand with the archaeologist, on site, the survey crew can also provide markers and other on-the-spot information for the archaeologist's immediate use. Where terrain is too rugged for use of the towed cart, the platform can be adapted for backpack operation by one or two men.

The automatic position-detection unit eliminates the need for time-consuming surveys of the site, and the laying out and staking of grids with consequent disturbance of the site. Time and cost requirements for an archaeology survey are therefore reduced, and the site is left undisturbed. Any kind of grid pattern can be chosen, and, since results are available in real time, areas of the site showing unusual subsurface features can be immediately re-explored using a tighter grid spacing to obtain more detail on subsurface features.

Subsurface radar is the most difficult sensor to use and presents the greatest quantities of data to be reduced. Therefore, to qualify for use with the most difficult sensor, the platform was initially built and tested around a family of radars developed at SRI during the past four years. Data processing and recording equipment, electrical power supplies, and cart storage space are at present provided by a mobile laboratory (Figure 3). All equipment can thus be driven to the archaeological site.

The potential usefulness of the platform has been initially demonstrated by a series of field experiments at Chaco Canyon National Monument, New Mexico, where subsurface structural features have been readily mapped by a subsurface radar mounted on the platform (Figure 4).

Archaeologists interested in joint research and cooperation in a survey of their site with this platform should contact Roger Vickers or Lambert Dolphin at [415] 326-6200, Ext. 4422 or 4868. To assist in archaeological evaluation of this technique, SRI is working in cooperation with Professor Ezra Zubrow, Department of Anthropology, Stanford University. Professor Zubrow is available to discuss archaeological applications of the platform and its potential usefulness, at [415] 497-3118.

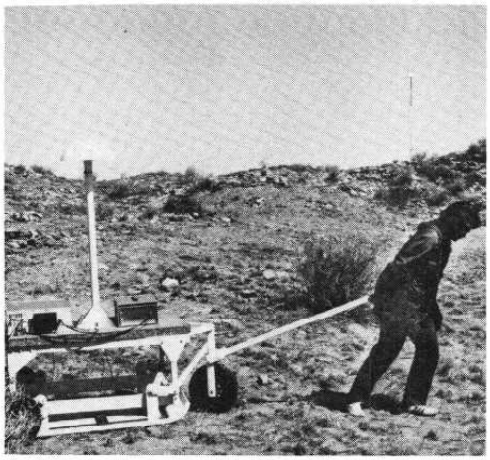


FIGURE 1

FIGURE 2

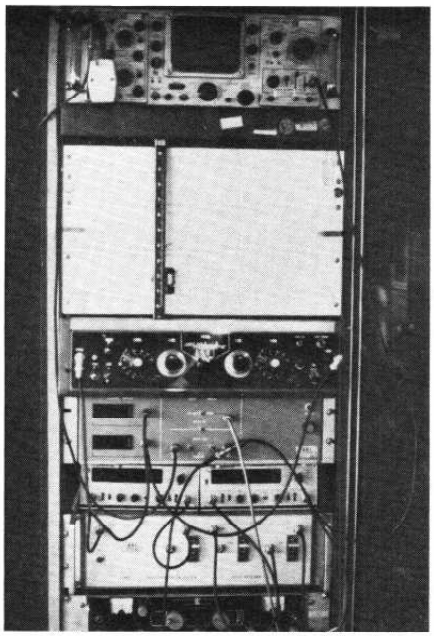
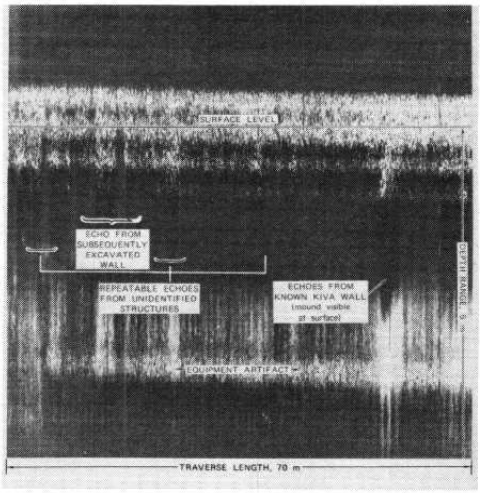


FIGURE 3


SURFACE LEVEL
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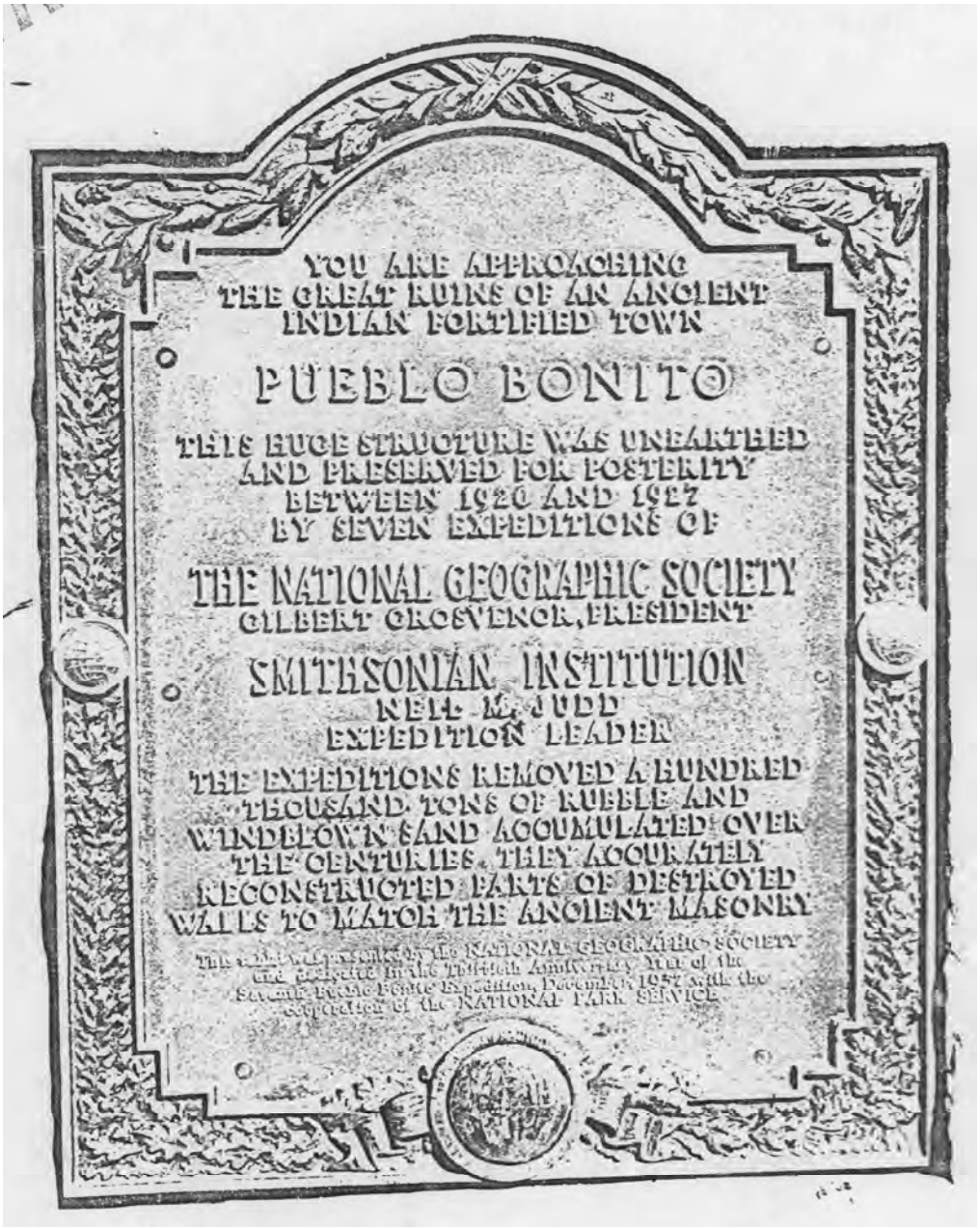
EQUIPMENT ARTIFACT
DEPTH, 5 m
TRAVERSE LENGTH, 70 m

FIGURE 4

# ARCHAEOLOGICAL INVESTIGATIONS AT CHACO CANYON USING A SUBSURFACE RADAR

R. Vickers, L. Dolphin, D. Johnson



ABSTRACT

The use of subsurface radar as a tool to aid in the exploration and surveying process in archaeology is described. Experiments spanning a period of three years are described, in which subsurface radar data were acquired at various sites within Chaco Canyon, New Mexico. The detection of masonry structures is illustrated, and the limitations of the technique are discussed.

The development of an all-digital radar system for archaeology, together with a precision position location system for use in radar surveys is described, and its use in a field survey is illustrated with examples from Chaco Canyon.

## I INTRODUCTION

Over the past three years, several experiments have been conducted in the use of subsurface probing radar for archaeologica1 exploration. A number of these experiments, reported here, were conducted at various sites within Chaco Canyon, New Mexico, for the purpose of evaluating the performance of subsurface radar when applied to archaeology. The original system used in these experiments was a ground-penetrating radar that was developed for use in locating underground utilities and shallow geologically related phenomena such as solution cavities, fractures, and voids. A natural outgrowth of this work was to use the radar system to investigate other man-made objects such as archaeological structures that may have suffered partial or total burial. This paper describes subsurface-radar principles of operation, use in the field, and data reduction.

## II PRINCIPLES OF SUBSURFACE RADAR

In their operating principles the radar systems that are used for subsurface work have a strong resemblance to shallow-reflection seismic systems; a short burst of energy at a selected frequency is transmitted into the ground and reflected energy is received from any interface or discontinuities within the range of the transmitter. The radar antennas are usually placed close to the ground and moved along in a continuous fashion, while the echoes are viewed on an oscilloscope face and simultaneously displayed on a facsimile recorder.

The major factors that affect the performance of the radar are:

(1) Conductivity of the soil

(2) Dielectric contrast between the target and the soil

(3) The shape of the target and its orientation with respect to the radar antennas

(4) Density of scattering bodies within the soil that produce echoes similar to those from the targets.

Of these, the one that places the greatest limitations on the use of radar in archaeology is the soil conductivity. This parameter is itself a strong function of water content and clay content of the soil. In general, soils with more than a few percent of moisture will attenuate radar signals too strongly for the technique to be useful. In contrast, however, we have found one example in Oregon where the soil moisture was high due to year-round heavy rainfall, and all the compounds causing ionic conductivity had been leached out of the soil. Because of the

importance of conductivity, in the investigation of a new site with radar it is recommended that soil samples be taken at depths of one to three feet in the area to be surveyed, and wrapped in moisture-tight containers before shipping for laboratory analysis of their electrical properties. In the case of Chaco Canyon, the results of laboratory analysis are shown in Table 1. The losses shown in this table are given in decibels per meter as a function of

*Decibels are logarithmic units. In the case quoted, the losses correspond to 10 times the logarithm (base 10) of the ratio: (power into the soil / power after propagating through 1m of soil).*

frequency. A good figure of merit to use for a subsurface radar is that it can detect return signals about 80 to 100 dB below the level of the transmitted signal. If typical values are used for reflection coefficients and antenna coupling efficiencies, a typical system could tolerate only 40 to 60 dB of loss in the ground. Thus, from Table 1, a soil with high clay content (Sample 3) from Chaco Canyon would cause a radar loss of about 22 dB/m at 100 MHz and would therefore limit the useful two-way radar range to 2 to 2.5 m.

It is easily seen from Table I that the losses increase with frequency, and that greater penetration would therefore be possible with lower frequencies. Unfortunately, other constraints make it unprofitable to operate at frequencies much below 100 MHz. The most important of these is resolution, which itself is directly proportional to frequency. At 100 MHz, the resolution that one might expect in typical dry soils would be about 0.75 m. Other constraints that make the low-frequency option unattractive are the increased antenna size required and the increased transmission time during which echoes cannot be detected. As a result of many experiments at a large variety of sites, we have concluded that the usable frequency range for archaeological radars when searching for near-surface structures is from 100 MHz to 400 MHz.

## III RADAR EQUIPMENT

A number of major features are common to all subsurface radars. Firstly, such radars all use resistively loaded antennas operating very close to, or directly on, the ground. Secondly, they all use a sampling oscilloscope to display the echo waveform and reduce the bandwidth of the data stream; and lastly, all such radar applied to surveying work use a recorder of the facsimile type for displaying the radar data. A simplified diagram of a subsurface radar operating at 400 MHz is given in Figure 1. In our earlier systems, all the equipment indicated, except the oscilloscope and the pulse generator, was mounted on a movable cart connected with two low-loss cables to the remaining instruments and data-recording devices. In some radars, the source was replaced by an avalanche transistor that was then used to shock-excite the antenna. This resulted in a much smaller system, and a resultant signal with different spectral characteristics from the design shown. In general, we have had more success with the modulated signal scheme shown in Figure 1, although this was not used until 1975 at Chaco Canyon.

In most cases of subsurface radar sensing, data processing subsequent to the survey can enhance the desired echoes from buried features, and can reduce the ambiguities in interpretation. For this reason, the profiling data are usually recorded on magnetic tape as well as on the real-time chart display. One further item of equipment that is very helpful in

radar surveys is a resistivity meter. This instrument, which is a standard geophysical tool[1], is used to measure the low-frequency resistivity of the soils at different effective depths. These data can be used to predict the performance of a given radar system in terms of its penetration, and can indicate any changes in operating frequency that would be advantageous. Resistivity profiles can also be taken in which the resistivity of the near surface is mapped as a function of horizontal position. When such a profile is taken over a known structure, the resistivity of the structural material can also be calculated. Figure 2 shows the resistivity instrument being deployed at Pueblo Alto. The total equipment is composed of four electrodes and a measuring system.

## IV OPERATING PROCEDURES

As mentioned, the first step in radar surveys is to obtain data on [the estimated attenuation of the soil; this is] usually accomplished by use of sample analysis in the laboratory. Knowledge of the electrical properties allows the operator to calculate the optimum radar frequency for that site, or indeed to determine whether a radar survey would be totally unsuccessful at any frequency. The second step is to obtain resistivity profiles over the area to verify that the in-situ bulk properties are the same as those predicted by laboratory measurement. An example of the data from such a profile is given in Figure 3, which was taken over a known masonry structure outside Pueblo Alto in Chaco Canyon. The anomalous resistivity of the wall can be clearly seen. Radar tests and traverses are then made. In past years these traverses have followed a rectilinear grid pattern at a spacing dictated by the local geography and the amount of ground cover that had to be removed. As will be described later, this limitation has now been eliminated. The last step in subsurface surveys is to reduce and interpret the data. Every effort must be made to perform some interpretation in the field at the time of the survey, since the correlation of surface expression, radar data, and unwanted surface targets (rocks, tree roots, or metallic refuse) is very important and cannot be duplicated after leaving the site.

## V RESULTS OF SURVEYS AT CHACO CANYON

### A. 1974 Survey

The first surveys at Chaco Canyon with radar equipment were conducted in 1974[2] and were made at Pueblo Bonito, Hungo Pavi, and several unnamed sites containing back-filled pithouses. The most striking results were obtained at Hungo Pavi, where the presence of man-made structures was easily seen in the raw data. Figure 4 shows data from a traverse over a city wall and into the plaza area of the pueblo.

To the best of our knowledge, the area traversed at this site was undisturbed, and extended across a prominent mound containing an extension of the main pueblo structure. The mound was some 5 to 6 m in width and was surmised to contain rooms as well as a portion of the city wall. The vertical extent of this record is abut 4 m and the horizontal extent about 8 m. Vertical structures with interconnecting horizontal members are clearly depicted and indicate a man-made origin. From the scale it is obvious that the horizontal sections are not the floors of successive stories as was first thought, but more probably different levels of

partially decayed walls.

The small echo to the upper left was marked during the traverse and subsequently excavated. The uncovered target is shown in Figure 5, and was the upper surface of a well preserved was about 15 cm below the surface. Despite the shallow burial, there was no discernible surface expression of this structure.

Other areas were investigated during this series of experiments, with varying results. These results were in general quite encouraging in that, in soils with low radar losses, masonry targets could often be detected, although known adobe structures with modern fill material were usually missed. In one particular case, where excavation and backfilling had preceded the radar survey, strong echoes were obtained over adobe walls, but it was not clear whether the echoes were due to the walls or to the difference in soil compaction due to excavation and backfilling procedures.

B. 1975 Survey

A second series of surveys was made in 1975 at the undisturbed site of Pueblo Alto. This site was ideal in that it had low radar losses, was comparatively level in the plaza area where we wished to work, and was scheduled for shallow excavation in the summer of 1976. Thus, any structures that were indicated by radar could be verified later by the excavation procedures. One traverse was made over the trash mound for the Pueblo, with predictably negative results. The radar showed nothing but numerous scatterers within the soil. In physical terms this indicated that no objects were present in the mound that were both different in dielectric constant and larger than about half a wavelength. (The frequency chosen for this survey was approximately 300 MHz, giving a value of 25 cm for one-half the wavelength in soil.) A survey was then made of the plaza using a grid spacing of 5 m, and grid lines 70 m in length. Several plots of the echoes were prepared, and one of these showing only the major echoes in an area 40 m by 70 m is given in Figure 6. The kiva shown on the left had considerable surface expression, and was used as a control in the search for similar echoes. The one on the right was surmised from the data, since in that region a disproportionately large percentage of the echoes lay on a circle. Based on this and other maps of lesser echoes, a number of locations were suggested to our colleagues at the Chaco Center for testing. Of the two that were tested, one (shown in Figure 7) contained near-surface masonry structures, and the other showed marked deformation of the soil strata (shown in Figure 8), indicating a possible wall at greater depths. The maps that were prepared with all echoes included proved to be confusing, in that the grid spacing was too coarse to allow the individual echoes to be connected with any confidence. It was concluded that a grid would be needed with spacing less than one meter to resolve this problem for the particular site in question. It was further noted that there was a natural tendency to interpret the echoes as being due to linear structures aligned with the traverse axes, a bias that is well known to the geophysics community in the interpretation of aerial line-profiling data. The only way to remove such a bias convincingly would be to conduct the surveys using a random walk pattern, but this causes problems in locating where each element of the data came from. The solution would be to have a continuously operating positioning system that gave accurate location data to be recorded along with the radar echo data. Such a system was built for the last series of surveys in 1976.

The work in Chaco Canyon also showed that the radar system and the associated recording and data reduction could be improved considerably if the cables connecting the radar cart to the electronics were removed, and an all-digital system was employed. Without the umbilical cables, traverses could be made over greater distances and rougher terrain, and the problems of having to identify and remove cable reflections and re-radiation from the data would be eliminated. It-was decided to develop and build a system in which the data would be transmitted via a telemetry link to a nearby vehicle equipped with a computer and display unit. At the same time, a position-location system built into the radar cart would provide an immediate capability at the computer for plotting the location of the radar traverses.

C. 1976 Survey

The system was field tested, again at Pueblo Alto in the spring of 1976. Since there was some doubt as to the moisture content of the soil, resistivity profiles were again made, this time across the center of the plaza. The soil was indeed found to be more lossy than in the previous year, but not enough to rule out the use of radar. After some preliminary testing, surveys were conducted at a frequency of 250 MHz, concentrating on several small areas of interest rather than trying to cover the whole plaza in great detail. The radar cart, shown in Figure 9, was traversed in a random manner over these areas while in a nearby mobile laboratory (Figure 10) the data were plotted and the position of the cart tracked simultaneously. An example of the track is given in Figure 11, where the cart position was plotted directly onto a contour map of the plaza. The "X"s indicate the position of the three antennas that had to be emplaced for position location. Since the scale of these plots is continuously variable, it is just as simple to plot the survey track onto an aerial photograph, which was indeed done at one point in the survey. The ability to view an actual photograph allows the operator in the vehicle to have a good appreciation of the survey at any given time, and to correlate any conspicuous echoes with terrain features. During the data acquisition, the computer operator signaled the cart team when an echo was occurring and a colored marker was dropped at that point. In this manner, the radar cart operator could see the buildup of echoes in any linear or circular pattern and would cross and recross the area to make sure that the gaps in the pattern were filled in, thus avoiding the interpolation problems of the previous year. An example of part of the survey area being filled in with echoes is given in Figure 12, from which it can be seen that a number of linear features are apparent. Again, these data are plotted from a random-walk survey pattern, and any linear features that show up at this site are hard to explain by any other means than the presence of a man-made structure.

While the automatic position-location system can presently locate any echoes to within plus or minus 30 cm, the vertical accuracy of the radar system is harder to define because of the interference between echoes from objects other than the target, or from different sections of the same target. From a classical radar point of view the accuracy at 250 MHz in Pueblo Alto was approximately 25 cm, but from experimental experience it was probably not better than half a meter. The echoes in Figure 12, for example, fell into two categories, one group was apparently just below the surface, perhaps 15 cm or so, and the other was between 1 and 1.5 m. It was not possible to excavate to this depth because of the excavation scheduled

for the following months.

Work is presently underway to program the computer to recognize echoes from different depths and to store their locations for later printout on overlays for each depth cell.

## VI CONCLUSIONS

The use of radar data to investigate the near subsurface of archaeological sites has been demonstrated. The technique suffers from a severe limitation in that the sites chosen must usually be dry so that the soil attenuation is low. Sites can generally be evaluated in advance of any radar field work by the examination of carefully obtained soil samples, or by the use of resistivity data. The radar technique can be used with success when the targets are near the surface, and have a contrast in dielectric properties from the surrounding soil. The work reported here all took place at Chaco Canyon, but a bank of representative data from other sites is being accumulated to allow better predictions to be made concerning potential radar performance, and to assist the data interpretation phase of subsurface surveys. The maximum depth of penetration observed so far at an archaeological site was 10 m at a frequency of 220 MHz. Typical depth penetration is from 1 to 4 m at frequencies over 200 MHz.

It is hoped to continue the work described here at other sites in the near future, and to further refine the radar techniques, perhaps combining it with complementary techniques such as acoustic sounding and magnetometry.

## ACKNOWLEDGMENTS

We wish to express our appreciation to Dr. Tom Lyons of the Chaco Canyon Center for his continual encouragement and assistance in the field, and to Dr. J. Judge, also of the Center, for his assistance in the 1975 survey. We would also like to thank the National Park Service at the Chaco Canyon National Monument for their cooperation during our repeated visits. Our thanks also go to Dr. Elizabeth K. Ralph and Bruce Bevan of the University of Pennsylvania Museum Applied Science Center for Archaeology for their participation in the experiments. Partial financial support from the University of Pennsylvania and the Chaco Center is gratefully acknowledged. Finally, belated thanks go to our many colleagues at SRI, particularly John Tanzi, Philip Bentley, and Bruce Craig, who donated much of their evening time to developing and testing our equipment.

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Table 1

RADIO FREQUENCY LOSSES IN FOUR SAMPLES FROM CHACO CANYON, NEW MEXICO

| Frequency (MHz) | Attentuation Coefficient (dB/m) | | | |
|---|---|---|---|---|
| | 1 | 2 | 3 | 4 |
| 10 | 0.24 | 0.20 | -- | 0.33 |
| 20 | 0.45 | 0.45 | -- | 0.64 |
| 30 | 0.60 | 0.66 | -- | 0.90 |
| 40 | 0.83 | 0.82 | -- | 1.2 |
| 50 | 1.0 | 1.0 | -- | 1.4 |
| 60 | 1.3 | 1.2 | 11.7 | 1.4 |
| 70 | 1.4 | 1.4 | 14.2 | 1.7 |
| 80 | 1.5 | 1.5 | 16.2 | 1.9 |
| 90 | 1.8 | 1.7 | 19.6 | 2.0 |
| 100 | 2.0 | 1.8 | 22.0 | 2.1 |
| 120 | 2.6 | 2.2 | 24.3 | 2.5 |
| 140 | 3.2 | 2.8 | 30.1 | 2.9 |
| 160 | 4.1 | 3.2 | 36.1 | 3.4 |
| 180 | 4.4 | 3.4 | 43.0 | 3.8 |
| 200 | 5.8 | 3.5 | 55.0 | 4.2 |
| 220 | 7.4 | 3.8 | 69.0 | 5.2 |
| 240 | -- | 5.1 | 86.0 | 6.2 |
| 250 | -- | 5.7 | -- | 7.5 |

Sample 1 Construction sandstone, Pueblo Alto, average dielectric constant, $\epsilon_r$ = 4.9 to 6

Sample 2 Alluvial sand, Pithouse E, $\epsilon_r$ = 1.7 to 2.1

Sample 3 Alluvial clay Chaco Wash, $\epsilon_r$ = 7.0 to 12

Sample 4 Alluvial loam below trash dump, $\epsilon_r$ = 1.6 to 2.4

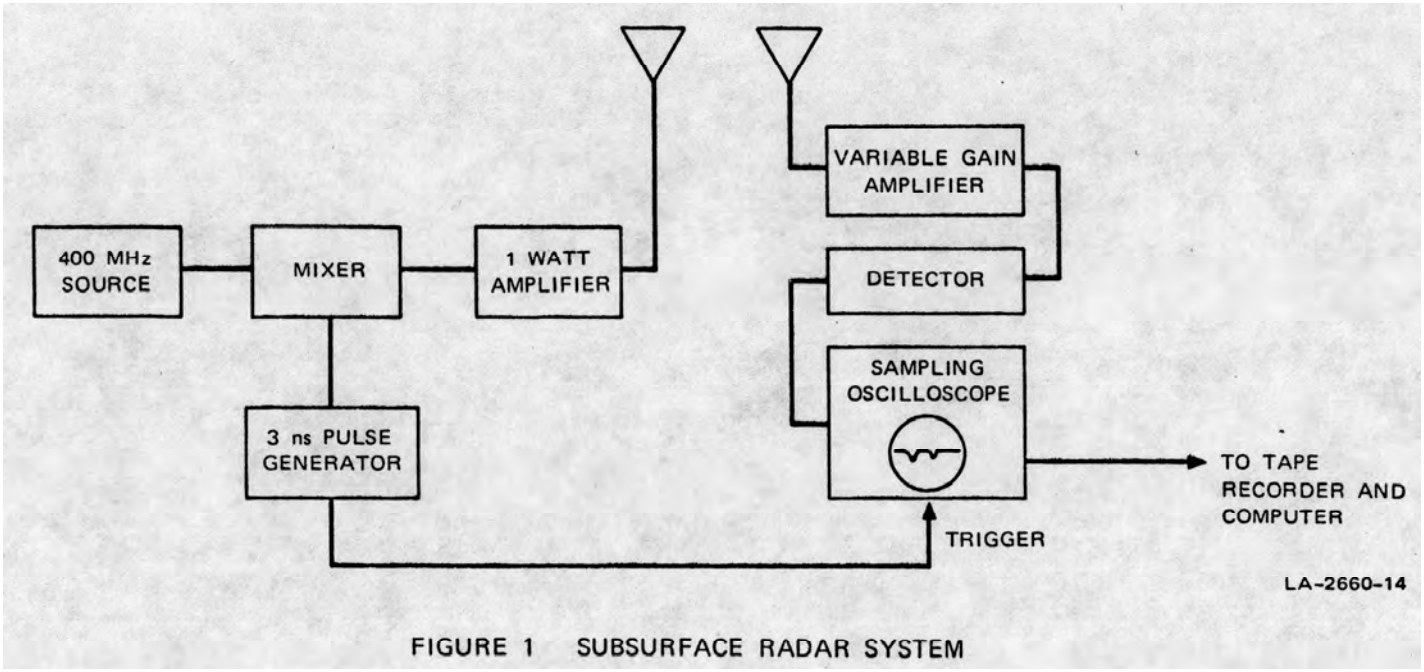


FIGURE 1 SUBSURFACE RADAR SYSTEM

FIGURE 2 RESISTIVITY PROFILE BEING CONDUCTED AT CHACO CANYON

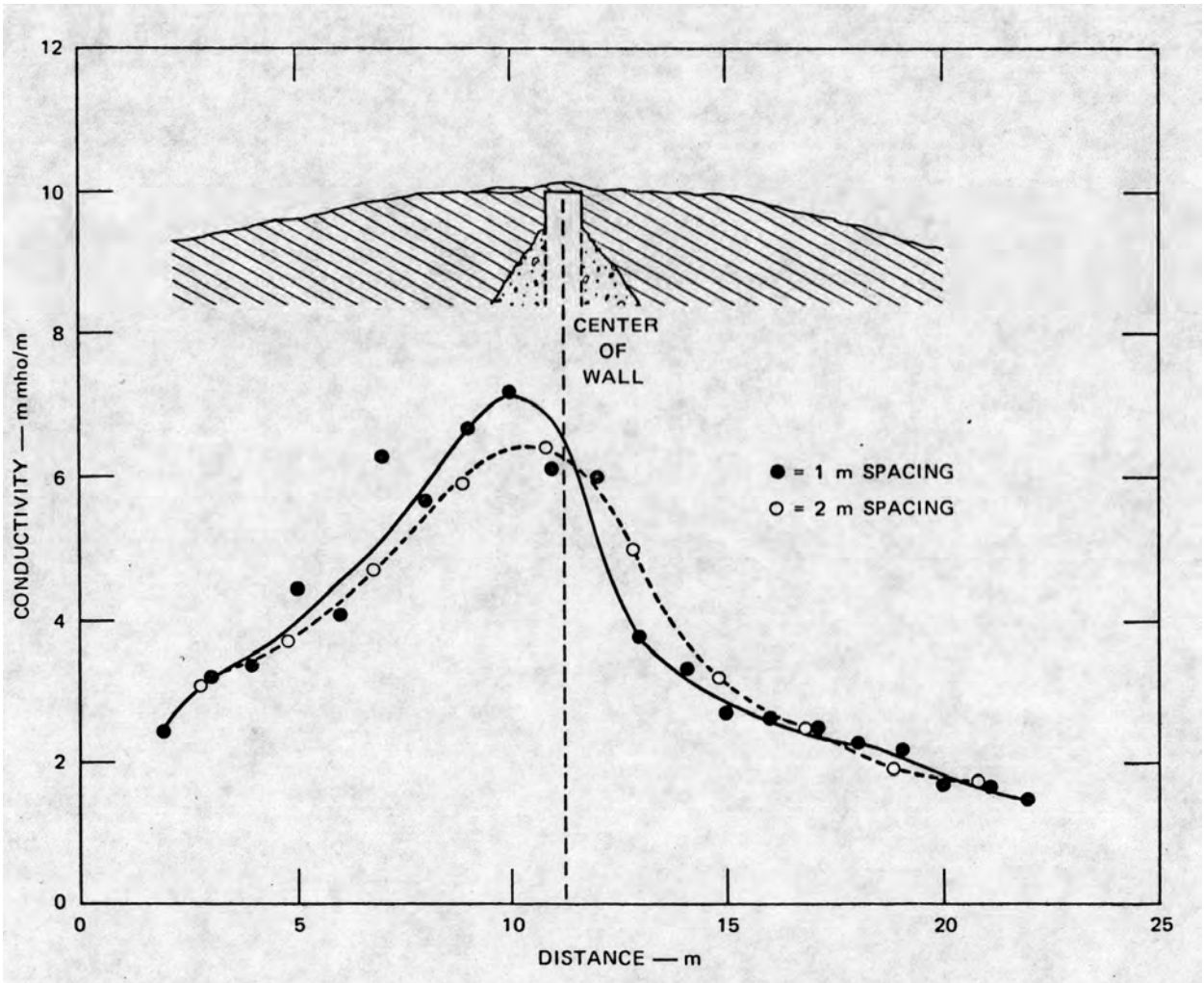


FIGURE 3 RESISTIVITY PROFILE ACROSS CAUSEWAY AT PUEBLO ALTO

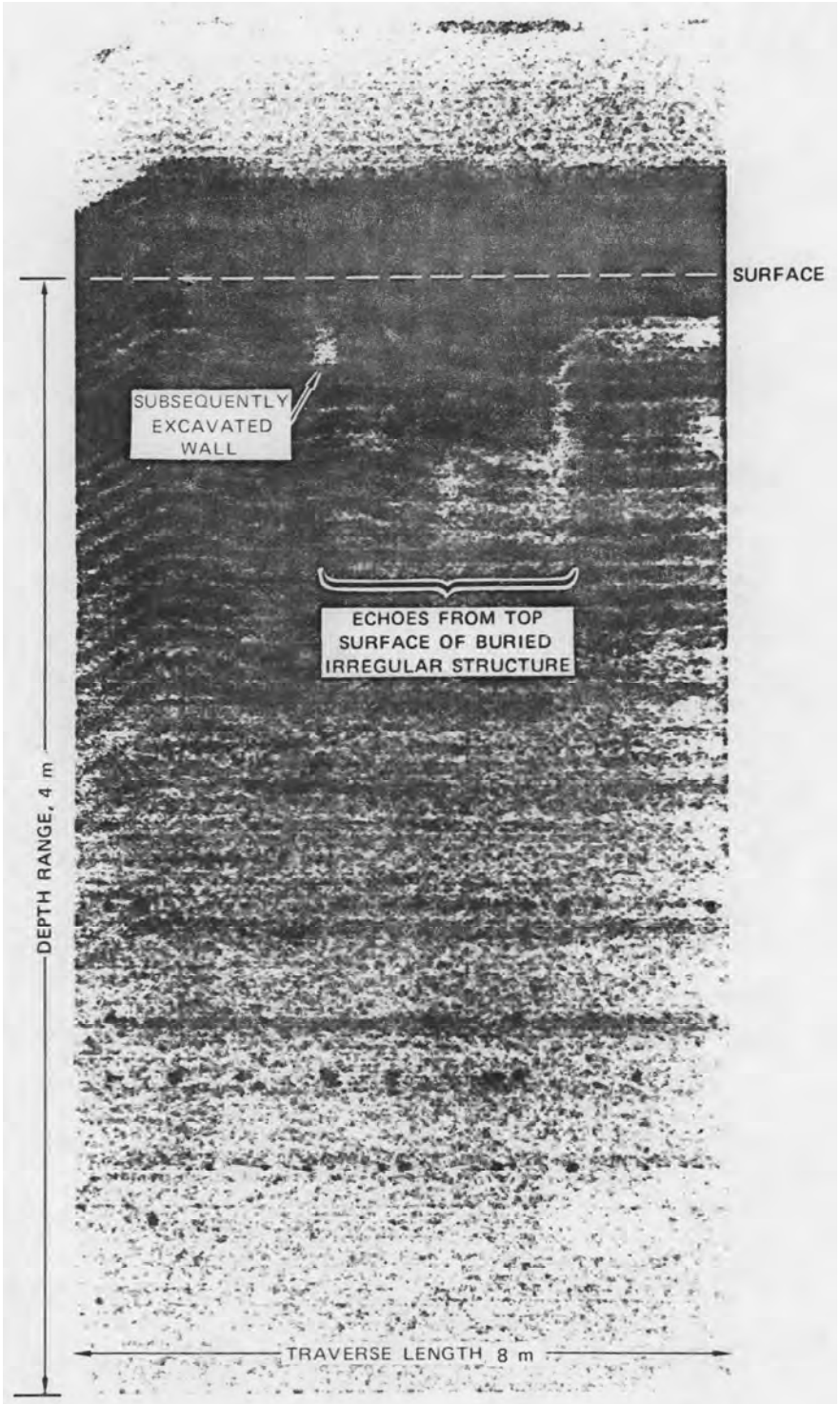
SURFACE
SUBSEQUENTLY EXCAVATED WALL
ECHOES FROM TOP SURFACE OF BURIED IRREGULAR STRUCTURE
DEPTH RANGE, 4 m
TRAVERSE LENGTH 8 m

FIGURE 4 RADAR ECHOES FROM SUBSURFACE TARGETS AT HUNGO PAVI

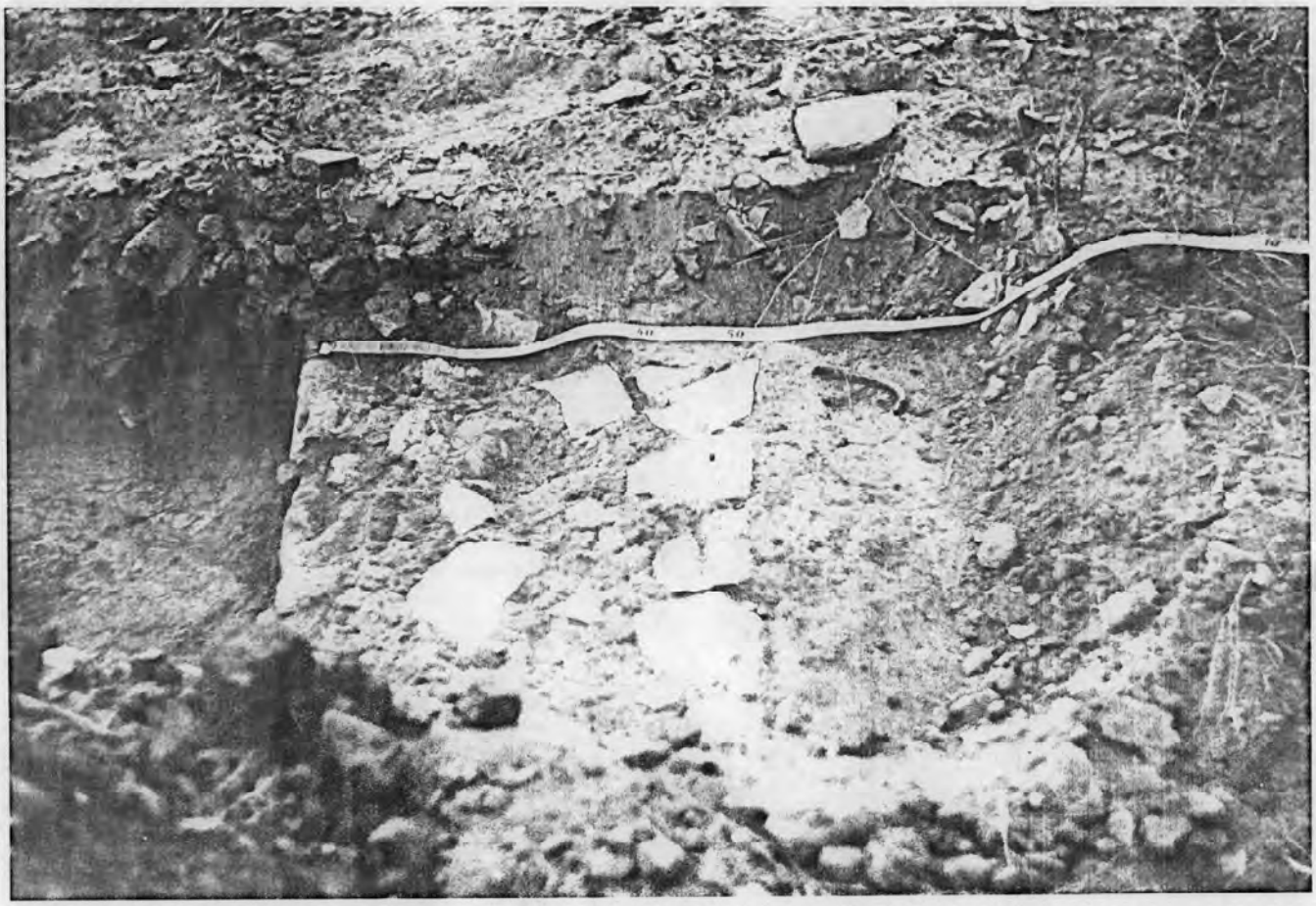

FIGURE 5 EXCAVATED WALL AT HUNGO PAVI

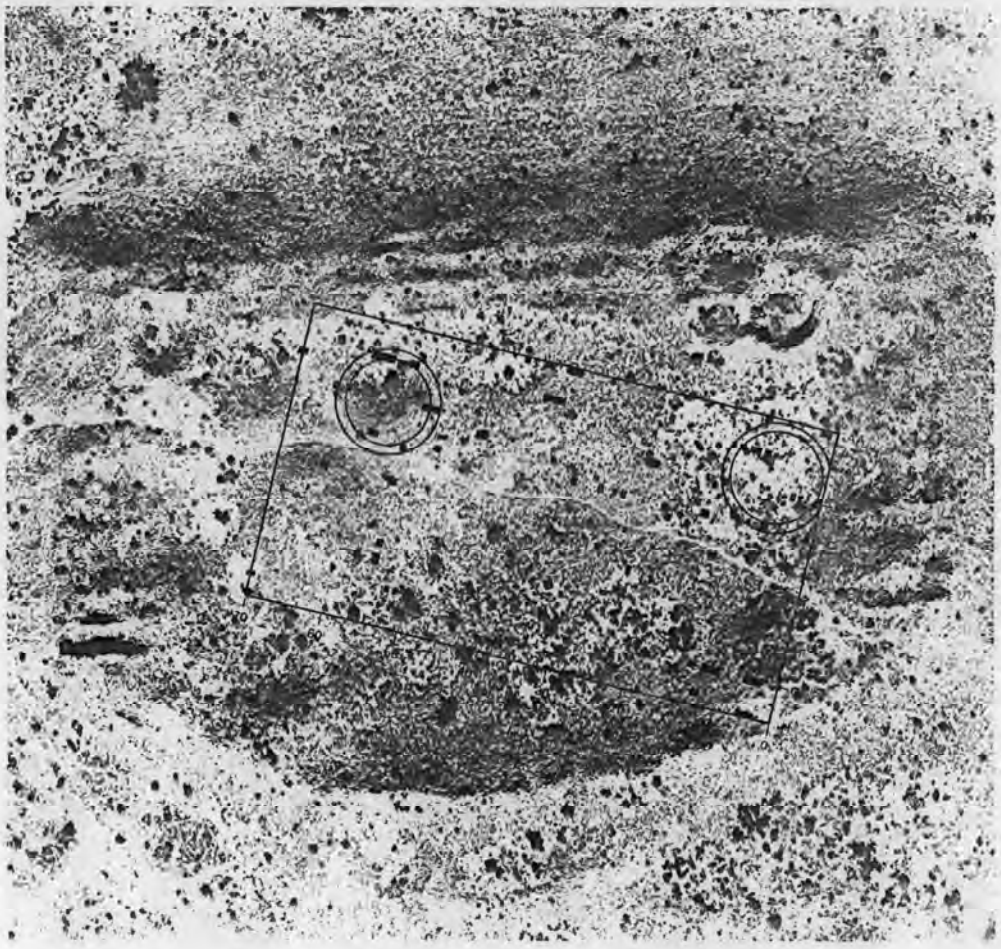

FIGURE 6 MAJOR ECHOES FROM RADAR SURVEY OF PUEBLO ALTO (distance in meters)

FIGURE 7 AREA UNDERLYING A MAJOR ECHO AT PUEBLO ALTO

FIGURE 8 AREA UNDERLYING A SUSPECTED KIVA ECHO, SHOWING CURVATURE IN THE STRATIFICATION

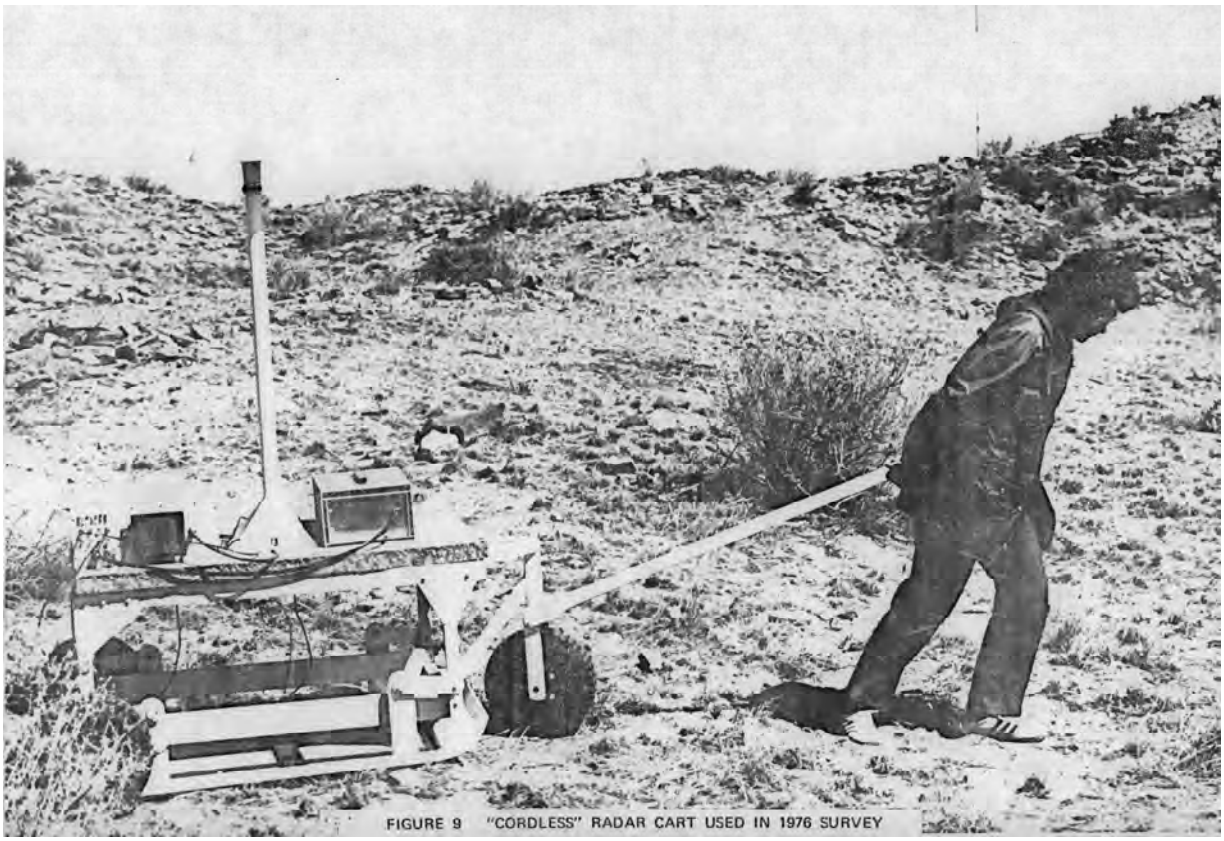

FIGURE 9 "CORDLESS" RADAR CART USED IN 1976 SURVEY

FIGURE 10 SRI's MOBILE RADAR LABORATORY

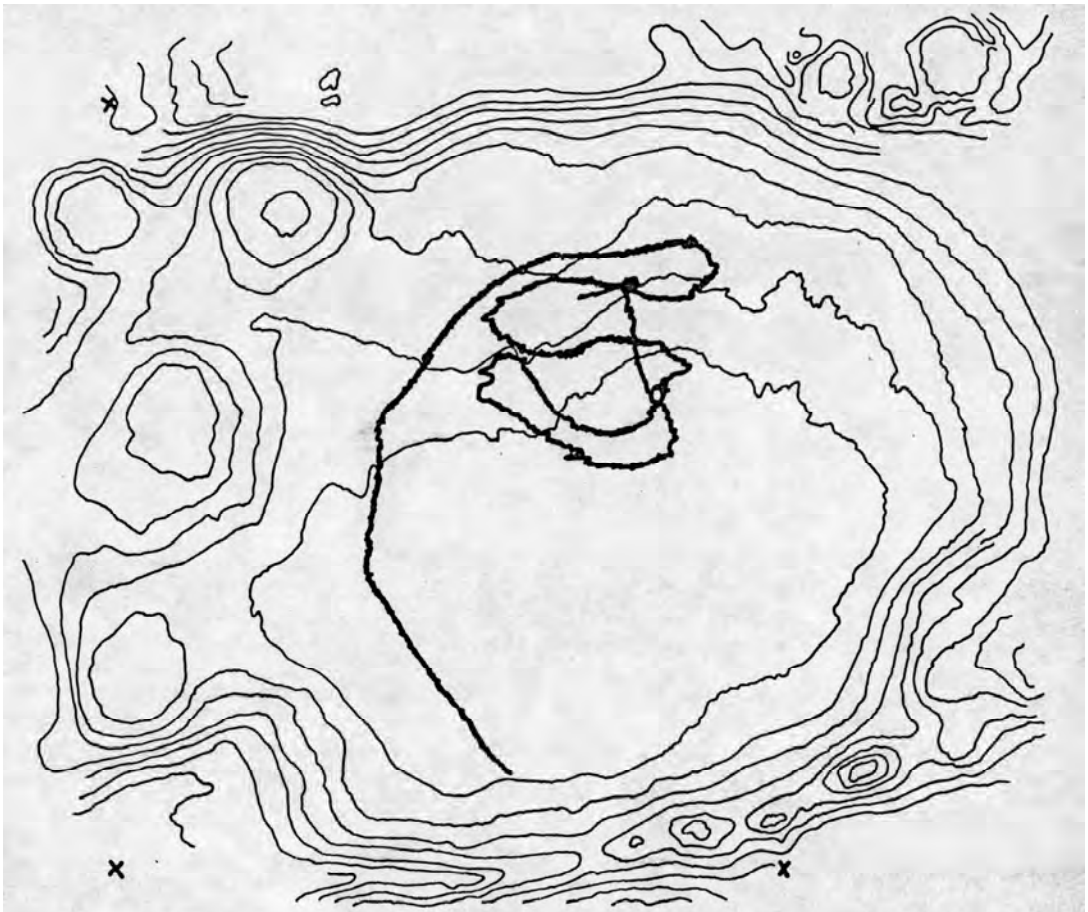

FIGURE 11 EXAMPLE OF POSITION-LOCATION SYSTEM OUTPUT

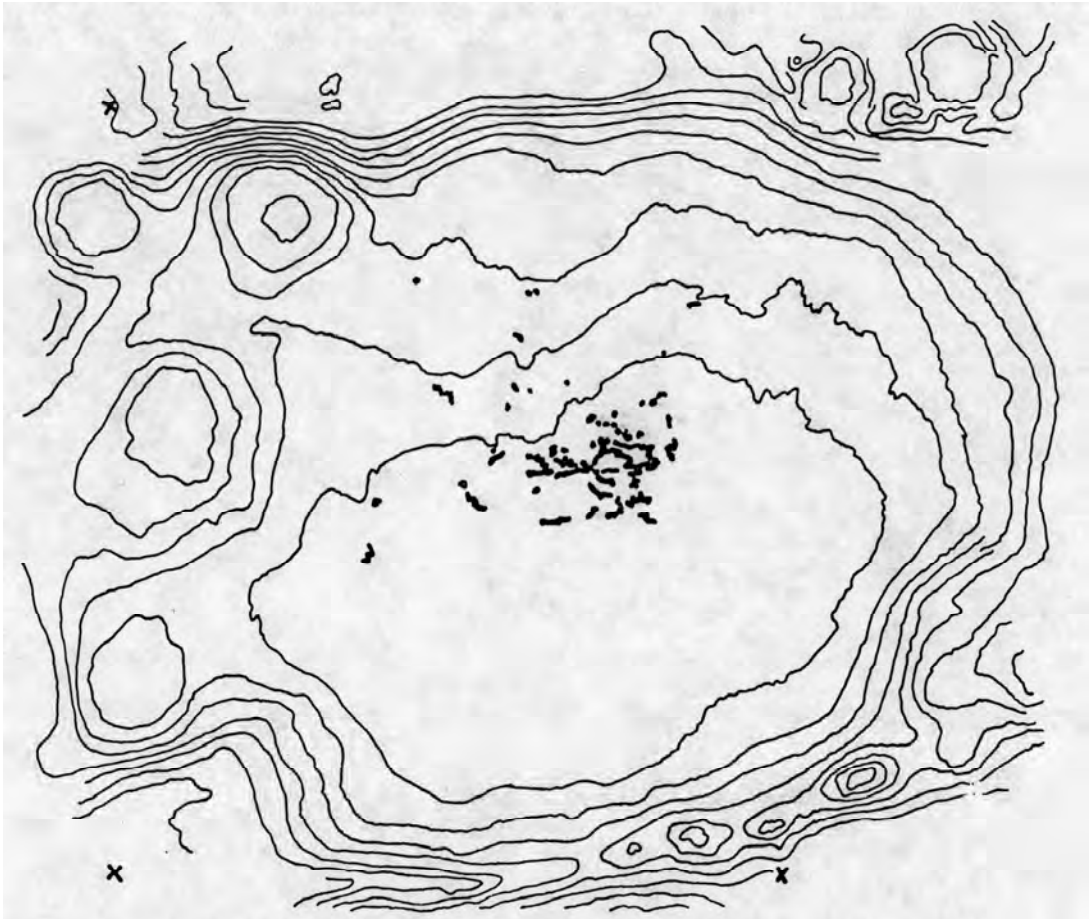

FIGURE 12 ECHOES OBTAINED IN THE CENTRAL PLAZA OF PUEBLO ALTO